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Quantity-Quality Simulation (QQS): A Detailed Continuous Planning Model for Urban Runoff Control. Volume I. Model Description, Testing and Applications

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Quantity-Quality Simulation (QQS): A Detailed Continuous Planning Model for Urban Runoff Control

Volume 1. Model Description, Testing, and Applications

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A comprehensive mathematical model, the Quantity-Quality Simulation (QQS) model, for calculation of urban stormwater and combined sewer overflow pollution and the means for its control is presented. The model operates in a continuous mode with a five minute time step and accounts for the unsteady runoff and overflow behavior of total drainage systems. Lumping techniques, that calculate the runoff from drainage areas, are combined with detailed flow routing through main and interceptor sewer as well as other structures such as branches, overflows, basins, pump stations, control gates, and treatment facilities. The computer program calculates the runoff in the storm or combined sewer and in the receiving waters. The program package, written in Standard Fortran IV, comprises approximately 30,000 statements. Applicability of the QQS model is demonstrated in a number of comparisons with measurements of runoff quantity and several water quality parameters made in several catchments. Short descriptions of QQS model applications are given for overflow abatement studies made for: Rochester, NY; Vancouver, BC, Canada; Toronto, Ont., Canada; Augsburg, Germany; and Munich, Germany.

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QUANTITY-QUALITY SIMULATION (QQS): A DETAILED CONTINUOUS PLANNING MODEL FOR URBAN RUNOFF CONTROL

Volume I

Model Description, Testing, and Applications

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development comprise that necessary first step in problem solution and involve defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies and for the minimization of adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of such research; a most vital communications link between the researcher and the user community.

This study describes the principles and use of the Quantity-Quality Simulation (QQS) model. The QQS model defines the impact of urban runoff on receiving waters and aids in the initial and detailed planning of abatement alternatives for pollution from storm sewer discharges and combined sewer overflows in urbanized areas.

Francis T. Mayo
Director
Municipal Environmental
Research Laboratory

PREFACE

Control of urban runoff pollution has become a focus of environmental protection activities. Satisfactory analysis of urban runoff abatement measures requires the investigation of numerous alternatives and planning variables to arrive at economical and efficient solutions. This has resulted in an increasing interest in the modeling of urban runoff.

Urban runoff models have been developed to serve one or more of the basic functions of planning, system analysis or design, and operations. A number of models were developed with only one of these functions in mind. Selection of a suitable model becomes a difficult task when two or more engineering functions are involved simultaneously. This situation is further complicated by the large variety of problems encountered in practice. A model serving multiple functions ideally should not produce more information than needed, yet should not yield such over-simplified results that its reliability is in question.

The simulation model detailed in this report was developed to serve multiple functions. It allows assessment of impacts of existing urban drainage systems on receiving waters as well as the evaluation of expected effects of structural and nonstructural mitigative alternatives. The model has been applied in the detailed planning and initial design of main system components and is considered to be applicable for the analysis of a wide variety of operations problems.

The theoretical background of this model and its data processing mode were developed during the period from 1973 to 1975. The programming was partially financed by the Federal Minister of Research and Technology of the Federal Republic of Germany (Grant No. 0825027).

Because this simulation model may well suit certain American needs within the framework of Section 201 and Section 208 studies, a research grant was provided by the U.S. Environmental Protection Agency to make this planning tool available to the American user. The model had already been used in an American city.

This report is in two volumes. Volume I describes the theoretical background, testing, and application of the model. Volume II is the user's manual for the model program.

Persons interested in acquiring a copy of the model program and the User's Manual (Volume II) should contact the EPA Project Officer through the Wastewater Research Division, Municipal Environmental Research Laboratory, Cincinnati, Ohio, 45268.

ABSTRACT

A comprehensive mathematical model, the Quantity-Quality Simulation (QQS) model, for calculation of urban stormwater and combined sewer overflow pollution and the means for its control is presented. The model operates in a continuous mode and accounts for the unsteady runoff and overflow behavior of total drainage systems. Lumping techniques, that calculate the runoff from drainage areas, are combined with detailed flow routing through main and interceptor sewers as well as other structures, such as branches, overflows, basins, pump stations, control gates, and treatment facilities. The computer program calculates the runoff in the storm or combined sewer system and in the receiving waters. The program package, written in Standard Fortran IV, comprises approximately 30,000 statements and can be used on any BATCH processing system having Fortran IV compilers.

While the QQS model is designed to operate in the continuous mode, single events may be used to calibrate and verify the model. A statistical analysis routine yields total monthly or annual runoff and overflow figures and related information such as the frequency and duration of receiving water loadings. Continuous simulations may be employed to assess a stormwater runoff, storm sewer outfall, or combined sewer overflow pollution problem and to estimate improvements that would be achieved by structural and non-structural control and corrective measures.

Applicability of the QQS model is demonstrated in a number of comparisons with measurements of runoff quantity and several water quality parameters made in several catchments. Short descriptions of QQS model applications are given for overflow abatement studies made for: Rochester, N.Y.; Vancouver, B.C., Canada; Toronto, Ont., Canada; Augsburg, Germany; and Munich, Germany.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

BOD_5	-- biochemical oxygen demand (5-day)
cfs	-- cubic feet per second
cts	-- counts
cts/5 min	-- counts per 5 minutes
COD	-- chemical oxygen demand
DEV	-- German standard methods for the examination of water, waste water and sludge
DWF	-- dry-weather flow
EPA	-- Environmental Protection Agency
FC	-- fecal coliform
ft	-- feet
g	-- gram
ha	-- hectare
hrs	-- hours
HVM	-- Hydrograph Volume Method
kg	-- kilogram
kg/5 min	-- kilograms per 5 minutes
km	-- kilometer
l	-- liter
l/s.ha	-- liter per second and hectare
lb	-- pound
m	-- meter
m^3	-- cubic meter
m^3/s	-- cubic meters per second
mg	-- milligram
mg/l	-- milligrams per liter
min	-- minutes
mm	-- millimeter
mm/5 min	-- millimeters per 5 minutes
N	-- frequency
P	-- phosphorus
Pb	-- lead
QQS	-- Quantity-Quality Simulation
R & D	-- Research and Development
s	-- second
SS	-- suspended solids
STP	-- sewage treatment plant
TSS	-- total supended solids
UWRR	-- Urban Water Resources Research
yrs	-- years
29.8.75	-- day.month.year, e. g. Aug. 29, 1975

SYMBOLS

A	-- flow area
a	-- subscript indicating upper end of sewer segment
b	-- subscript indicating lower end of sewer segment
c_1, c_2, c_3	-- coefficients defining pollutant build-up function
d	-- time of the day
$d..$	-- differential of ..
$\partial..$	-- partial differentiation
DTI	-- function of diurnal variation of pollutant wash-off due to land-use
η	-- fraction of pollutant load parcel
g	-- acceleration of gravity
h	-- water depth above weir crest
i	-- sequence number
H	-- flow depth
H_v	-- height of profile
I	-- precipitation intensity
I_{de}	-- surface depression storage
I_{eff}	-- effective precipitation
I_{ev}	-- evaporation loss
I_{si}	-- soil infiltration loss
I_{st}	-- precipitation loss at beginning of rainfall (I_{de} and I_{we})
I_{tot}	-- total precipitation
I_{we}	-- wetting loss
l	-- weir length
L	-- length of an element
μ	-- overflow weir coefficient
n	-- index in x-direction
P	-- pollutant load
P_{up}	-- pollutant build-up
P_c	-- pollutant load of drainage area runoff and DWF
Q	-- flow rate
Q_c	-- drainage area runoff including DWF
Q_n	-- uniform flow
Q_o	-- overflow rate
Q_v	-- full flow capacity
RDI	-- function for decrease of pollutant wash-off with increasing rainfall duration
S_f	-- friction slope
S_o	-- invert slope
t, τ	-- time
u, ϕ	-- unit impulse response
v	-- flow velocity
x, ξ	-- coordinates
Y	-- invert elevation
z	-- number of time steps of 5 minutes
1	-- subscript indicating time 1
2	-- subscript indicating time 2

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SECTION 1

INTRODUCTION

CONSIDERATION OF URBAN RUNOFF IN PLANNING

Control of urban runoff pollution has become a new focus for water pollution control agencies. The basis for this control is to establish the impact of stormwater runoff and combined sewer overflows on receiving waters. To accomplish this objective by observations alone, runoff and overflows would have to be monitored for a long sequence of events, with water quality samples taken over short time intervals. Observations of all intermittent loads from the immense number of storm sewer outfalls and combined sewer overflows usually found in an urban drainage system would be technically and financially impractical.

Even if such a data base were available, only existing conditions could be assessed. More importantly, it would not be practicable to determine the reasons for a combined sewer overflow occurrence, to select satisfactory measures for the improvement of storm sewer discharge and combined sewer overflow abatement, or to assess the impact of projected land use on receiving waters. Satisfactory analysis of urban runoff abatement measures requires the investigation of numerous alternatives and planning variables to arrive at economical and efficient solutions. Consideration of this factor has resulted in an increasing interest in modeling urban runoff, including its impact on receiving waters. The utility of urban runoff modeling was debated at length at a national symposium (14).

Urban runoff models have been developed to serve one or more of the basic engineering functions of planning, system analysis or design, and operations. A number of models were developed with only one of these functions in mind (1, 3 and 5). Features of major models have been compared by several authors (1, 6, 8 and 12).

Selection of a suitable model becomes a difficult task when two or more engineering functions are involved simultaneously. This situation is further complicated by the large variety of problems encountered in practice. Ideally, a model serving multiple functions should neither produce more information than needed, nor yield such over-simplified results that its reliability is in question.

This report is about the Quantity-Quality Simulation (QQS) model developed to cover the overlap in objectives and to yield the desired amount of information. This model not only computes runoff hydrographs at any location in a drainage or receiving water system, but also determines frequencies, volumes and durations of storm sewer discharges and combined sewer

overflows. Frequencies and durations of receiving water loadings are major parameters required for determination of urban drainage impacts on receiving waters. The ability to assess such impacts for existing systems and to predict the effects of structural and nonstructural alternatives for future systems aids in the initial and detailed planning and design of abatement facilities.

The reasoning behind the QQS concept may be explained as follows:

CONTINUOUS SIMULATION CONCEPT

Because rainfall is a stochastic process, the quantity and quality of runoff resulting from rainfall also have stochastic properties. In addition to the stochastic nature of precipitation, mainly two other variable factors influence the quantity and quality of runoff: (1) surface depression capacities and sewer network detention capacities, which may be fully or only partly restored after a prior rainfall; and (2) the amount of removable surface pollutants and sewer sediments, which depend on the magnitudes and patterns of preceding rainfalls and the durations of intervening dry-weather periods.

Therefore, the resulting storm sewer discharge and combined sewer overflow quantities and pollution loads also have random behaviour patterns. Also, because of these many influences and interdependences, the assigned frequency of a given rainfall event and the frequencies of sewer network flows and discharging and overflowing water quantities and/or overflowing pollutant loads resulting from a given rainfall event may differ from one rainfall event to another and with respect to each other.

Therefore, it is not feasible to establish a representative one-event design case (design storm) or a short series of events which by way of a limited number of single event calculations would allow judgment on quantity, frequency and duration of storm water runoff and receiving water pollution emanating from an urban drainage system. Also, it does not suffice to examine only those events which would cause overflow activity because: (1) these events are unidentified a priori; and (2) the rainfalls and dry spells which occur between overflow events change the initial conditions, which must be known in order to proceed with sewer network flow simulations. These conditions include: surface depression capacities, soil infiltration capacity, amount of removable pollution, retention potential in the sewer network, etc.

A continuous simulation of all effective rainfall events together with their associated runoff events is required to meet the main objective, i.e., the definition of reliable numerical conditions for storm sewer discharge and combined sewer overflow simulations. Results from continuous simulations are prerequisites for the statistical analysis of criteria which allow assessment of the overflow activity of a sewer network, such criteria being: frequency and duration of overflow quantities and loads of pollution constituents discharged, such as BOD_5, total suspended solids, settleable solids, fecal coliform bacteria, etc. Furthermore, peak, mean, and total dis-

charge and overflow amounts may be derived from continuous simulations. These values may be extracted for any desired span of time, such as for a total year, the summer months, or an individual month.

Thus, the availability of all discharge and overflow data makes it possible to define receiving water loading by determining loading frequencies and loading durations as well as the coincidence of storm sewer discharges and combined sewer overflows with the corresponding receiving water flows and background pollution. Moreover, frequencies and durations of phases during which regulations would be violated may be scrutinized (e. g., when water quality standards are exceeded).

The objectives of a given project dictate the required scope and content for the statistical evaluation of data generated by continuous simulations. For example, a considerable annual loading might be acceptable for aquatic life in flowing waters provided the loading enters continuously and at low concentrations, whereas intermittent loadings at high concentrations might prove fatal to such life forms. On the other hand, consideration of intermittent concentrated inputs would be less important than the determination of total annual load when a standing water body is involved.

As opposed to continuous simulation, single event or design storm simulations cannot provide loading frequencies or durations or total annual loadings. Nevertheless, single event simulations applying suitable design storms are adequate if the objective of a study is confined to the sizing of sewers. In this case, the design event should be selected in such a way that it represents patterns and characteristics of local rainfall and takes into account specific properties, such as total precipitation, peak intensity, time elapsed from start to peak intensity, precipitation volume before and after the peak, etc. Detailed hydraulic sewer system calculation methods and corresponding computer programs are available for the hydraulic design of sewer networks (1, 3 and 10).

UNSTEADY-STATE SIMULATION CONCEPT

Changes in the storm runoff from urban areas and the resulting discharges and overflows are phenomena which exhibit rapid variations, especially for periods of peak flow. Unsteady-state simulations of the rainfall-runoff process using half-hour time steps or even longer calculation intervals have been proposed; however, the inherent averaging of such methods would conceal the peaks and such simulations, therefore, are not suited for the definition of peak flows and peak loadings. Unsteady-state simulations applying coarse time steps would tend to underrate total runoff and overflow volumes and pollution loads. On the other hand, overrating may follow from using simplified steady-state calculation formulas, which may result in costly over-dimensioning of sewer facilities with the incorporation of a resultant, but unknown, factor of safety.

Storm sewer discharge and combined sewer overflow behaviour is strongly related to momentary flow processes and the momentarily available detention capacity of the sewer network itself. Not only the ambient detention capabi-

lity of the network and its structures must be accounted for in the simulations, but also the causative backwater phenomena. Also, other components of a network such as sewer branchings and connections, overflow chambers, detention basins, pumping stations, and control gates, must be simulated realistically. All of this can be accomplished in practice only by applying an unsteady-state simulation method which discretizes the rainfall-runoff process into short time steps, generally in the range of five to ten minutes.

Another factor contributing to unsteady and nonuniform runoff behaviour is the typical movement of rain cells across an area with simultaneous temporal and spatial variations in rainfall intensity. For example, in examining storms from a 20-year rainfall record for three rainfall stations in Munich, Germany, it was found that in addition to a local variation of intensities there was an average of 60-minute rainfall migration time from the westerly station over the central to the easterly station. During the traveling process the peak intensity shifted toward the end of the rainfall. These results confirm that rainfall and runoff variations with respect to location and time must be considered when dealing with study areas that encompass total cities or metropolitan areas.

CONSIDERATION OF AN ENTIRE SYSTEM

It is essential to study a sewer system in its entirety if mutual interdependences of individual system components and interrelationships between network, runoff and overflow behaviour are to be taken into account. Likewise, consideration of the entire system is required in order to select an overall effective and economical program of improvements. At the same time, such an overall consideration provides a basis for optimum system operation.

THE QQS CONCEPT

The QQS model was designed to permit continuous simulation of various rainfall series of several years duration together with discretization of the simulation into 5-minute calculation intervals. However, in order to do this at acceptable computer costs it is necessary to refrain from modeling each sewer length in detail. Therefore, a study area is subdivided into 30 to 100 ha (75 to 250 acres) drainage areas. The division of a study area into larger or smaller drainage areas depends mainly on the study objective, but it also depends on the system geometry. If the objective is to estimate the overall impact of runoff from an urban area on receiving waters, a coarser division into larger drainage areas may suffice. A finer division is necessary, however, for system component design or proof of compliance with stream standards for individual storm discharges or combined sewer overflows and also for looped and complicated sewer networks. The individual drainage areas may be assigned one of four different area-types, e. g., residential, commercial, industrial, or special.

Quantity of runoff from a drainage area is calculated according to the Unit Hydrograph method, separately for the impervious and the pervious por-

tions. Pollutant runoff from the drainage area is determined by modifying the unit hydrograph to include pollution related parameters.

Hydrographs and pollutographs are added to their dry-weather flow equivalents. The results are the quantity and quality inputs to the major sewer system, which usually consists of the main sewers and their interceptors and structures. Simulation of flow through the main sewer system is based on a solution of the kinematic wave equations, whereas the pollution transport is treated as a plug flow. This procedure accounts for the substantial effects caused by detention and backwater.

Figure 1 illustrates the concept of linking the calculated lumped runoff from individual drainage areas to the detailed flow simulation in main sewers and structures. The extent of division into input drainage areas is, however, subject to the study objectives and the system geometry as mentioned above.

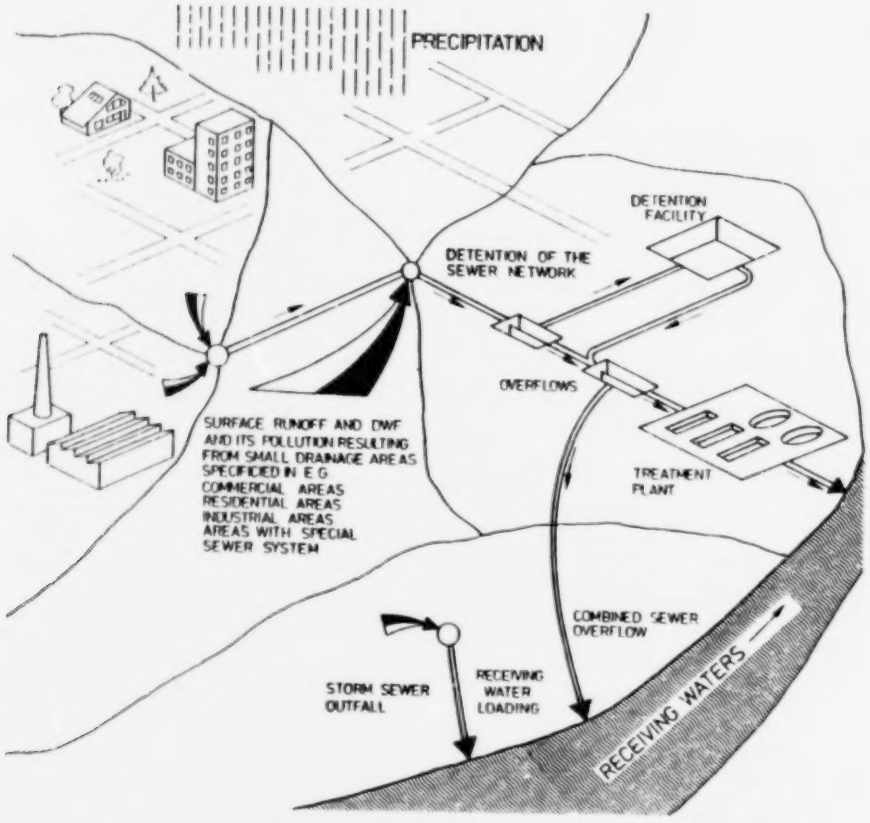

Figure 1. Abstracted view of urban system used for QQS.

Storm sewer discharges and combined sewer overflows and their respective pollutant loads represent the inputs to the receiving water. They are super-

imposed on the base flow and background pollution of the water body and then followed through the receiving water system by applying the same principles used in the major sewer system simulation.

According to experience, it is sufficient to simulate continuously the rainfall-runoff of a number of carefully selected representative years rather than a complete long series of 20 years or so, in order to determine storm sewer discharge and combined sewer overflow behaviour of a drainage system and the subsequent water quality characteristics of a receiving water body. The data resulting from a continuous simulation are subjected to a statistical analysis which produces, apart from totals, annual and monthly frequencies and durations of flows and pollutant loads and their concentrations, at locations such as detention basins, pumping stations, overflow structures and selected sections of the receiving water body.

Single event simulations may be carried out in addition to continuous, long-term simulations. They may cover either the total scope of quantity-quality simulation or quantity simulation only. Single event simulations are suited for comparisons between calculated and observed hydrographs and pollutographs and, if desired, also for comparisons with calculations made in a more detailed way by means of strictly hydraulic models such as the Hydrograph Volume Method (HVM), a proprietary model of Dorsch Consult (10). Another objective of single event simulations may be to determine the behaviour of a trunk sewer system for a design storm, a critical rainfall, or other single rainfall event. Although such single event simulations do not produce sufficient data to assess receiving water pollution, they may be utilized for the design and analysis of alternative improvements, for the examination of intermediate phases of sewer system construction, and for studying the effects of land use changes, as far as the major sewer system and its structures are concerned.

A detailed description of the individual components of the QQS method is presented in Section 2.

SECTION 2

HYDROLOGICAL BACKGROUND

RUNOFF FROM DRAINAGE AREAS

Runoff Quantity

Quantity of Storm Runoff--

Storm runoff from drainage areas is calculated using the Unit Hydrograph method. The validity of this method is maintained because its application in the QQS model is confined to small drainage areas where any distortions of the runoff hydrographs, which might be caused by backwater effects on the runoff surfaces or in the lateral sewers, are usually negligible. Moreover, utilization of this "black box" method has proved to be sufficiently accurate in small test areas of homogenous land use. If impervious and pervious area portions are considered separately, a comprehensive, mathematically linear runoff relation can reflect runoff behaviour from urban areas as well as from contiguous undeveloped areas.

The computer time and core requirements are substantially less than for the application of a hydrodynamic mode of runoff calculation because the transformation relation, i. e., the unit hydrograph, is of a relatively simple mathematical nature. In reality, this simplification makes it feasible to apply the QQS model to continuous simulations over extended periods of time.

A linear system is defined by its transformation relation. If the runoff portion of the precipitation, i. e., the effective precipitation, $I_{eff}(t)$, and the transformation relation, $u(t-\tau)$, are known, the precipitation-runoff relation may be represented by the convolution integral:

$$Q(t) = \int_{o}^{t} u(t-\tau)\ I_{eff}(\tau)\, d\tau \qquad (1)$$

where Q (t) is the drainage area runoff hydrograph ordinate value at time t (Figure 2). The transformation $u(t-\tau)$ may either be derived from rainfall-runoff observations or may be developed synthetically.

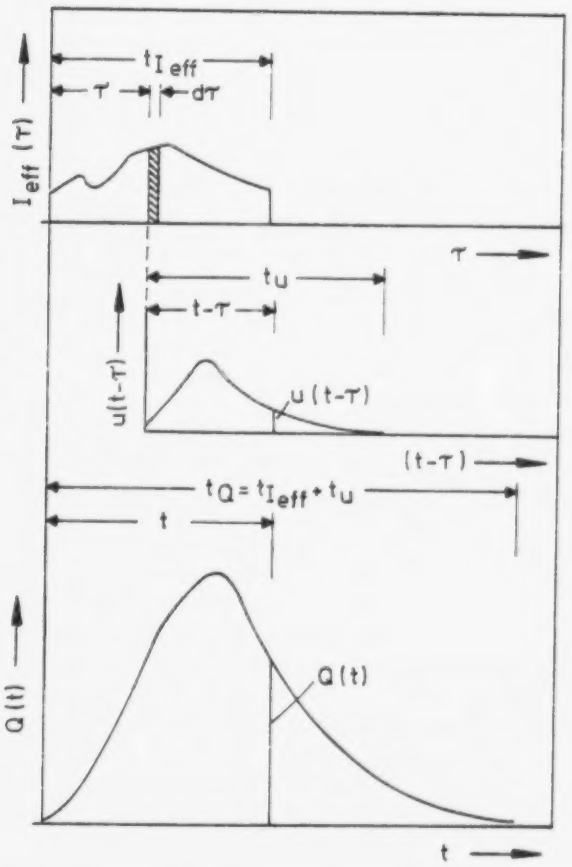

Figure 2. Unit hydrograph principle for quantity of storm runoff.

In addition to linearity, these two prerequisites must apply:

- The properties of the drainage area in question do not vary with respect to time
- Precipitation is uniformly distributed over the drainage area, a reasonable assumption for small sized watersheds.

The principle of linearity does not permit accounting for backwater effects which might be present on the surface and in the lateral pipes of the drainage area. Still, the adoption of the unit hydrograph as part of the QQS concept is regarded as a realistic decision, because the drainage areas as defined are of small size and normally include only minor sewers.

The effective precipitation, $I_{eff}(t)$, is determined by subtracting the losses from the gaged total precipitation, $I_{tot}(t)$:

$$I_{eff}(t) = I_{tot}(t) - I_{ev}(t) - I_{we}(t) - I_{de}(t) - I_{si}(t) \quad (2)$$

where I_{ev} = evaporation loss
I_{we} = wetting loss
I_{de} = surface depression storage
I_{si} = soil infiltration loss.

Apart from the evaporation, wetting, and depression losses which occur on impervious areas, soil infiltration losses are effective on pervious areas so that the determination of effective precipitation differs for impervious and pervious areas. Evaporation is accounted for in the QQS model only during dry spells, whereas it is neglected during a rainfall event because of its slight influence at that time. Decrease or increase in effective precipitation because of snow retention or snowmelt, respectively, is not considered in the present model. Studies of Pfeiff (15) and Brunner (2) carried out for Ludwigshafen and Munich, Germany, respectively, showed that for the areas investigated the bulk of storm and overflow events occurred during the summer months. Where this situation is true for a given study area, simulation of rainfall-runoff events for the summer months might be adequate.

Furthermore, it is presumed that wetting and depression losses are effective at the beginning phase of a rainfall. Therefore, these losses are combined into an initial or starting abstraction, I_{st}.

Soil infiltration is simplified by considering it as a constant loss which does not vary with respect to time. The reason for this assumption is computing costs and appears to be justified so that continuous long term simulations may be performed economically.

For impervious areas equation (2) above is thereby reduced to

$$I_{eff}(t) = I_{tot}(t) - I_{st}(t) \quad (3)$$

and for pervious areas to

$$I_{eff}(t) = I_{tot}(t) - I_{st}(t) - I_{si}(t) \quad (4)$$

Figure 3 is a schematic representation of the losses from precipitation as they are applied in the QQS model.

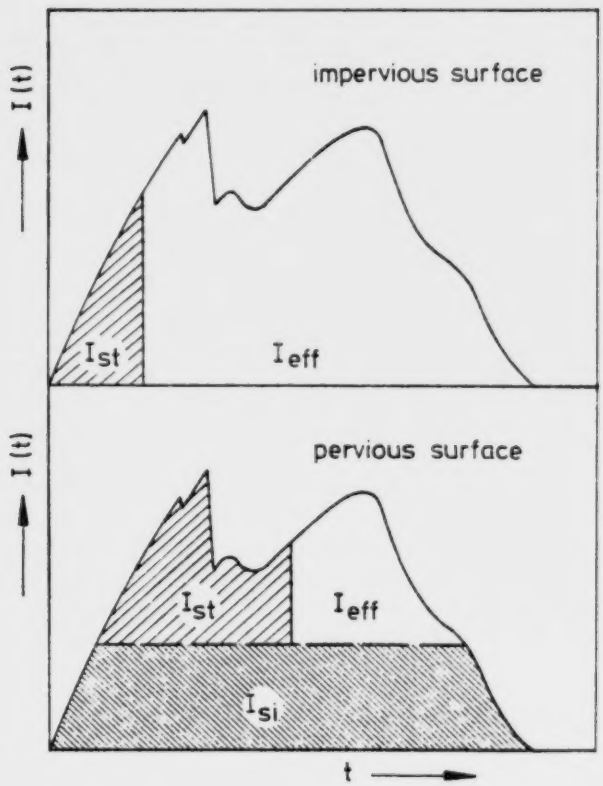

Figure 3. Determination of effective precipitation in the QQS model.

The storm runoff calculation from drainage areas not only distinguishes between impervious and pervious surfaces, but also among four different land use types (e. g., residential areas, commercial areas, industrial areas, or areas with a special drainage system).

Initial or starting loss values for the impervious portions of the different land use types are derived from measured events by establishing volume balances between observed precipitation and observed runoff. Reference figures for initial or starting losses are given for various land use types in Table 1. These figures are based on experience and have been extracted from a number of precipitation-runoff observation evaluations by the authors (the number of such evaluations is given in Table 6) and are backed by values that have appeared in the literature.

TABLE 1. REFERENCE VALUES FOR INITIAL OR STARTING LOSSES ON IMPERVIOUS SURFACES

Land Use	Initial or Starting loss (mm)
Commercial	0.5 to 2.0
Residential	0.7 to 2.5
Industrial	1.0 to 3.0

Pervious surfaces also have differing initial or starting losses depending as well on the land use. The same is true for the soil infiltration losses of pervious surfaces which, in addition, are a function of soil type. Initial or starting loss values for pervious surfaces may be determined by establishing volume balances, as for impervious surfaces, but in this instance soil infiltration must also be taken into account. Table 2 lists reference values for both initial or starting losses and soil infiltration values for various types of pervious surface.

TABLE 2. EXAMPLES OF REFERENCE VALUES FOR INITIAL OR STARTING AND SOIL INFILTRATION LOSSES FOR PERVIOUS SURFACES

Land use Soil surface characteristics (Typical examples)	Initial or starting loss (mm)	Soil infiltration (l/s ha)		
		Clay	Clayey sand	Sand, loess, gravel
Open space	10	20	30	40
Cultivated soil (corn, root crops, viniculture, hop culture, etc.)	8	10	20	30
Landscaped strip, playground	2	5	10	10
Protected green areas and slopes	5	20	30	50
Garden or meadow	5	20	30	40

Precipitation data are the most substantial input to storm runoff calculations. They may be extracted from tabulations of local, regional or national meteorological services.

Initial Conditions--

The filling and emptying of surface depressions and the soil infiltration that affects pervious surfaces are tracked by balancing each calculation time step. Because the duration of the dry-weather period preceding the rainfall in question is known, evaporation and infiltration which occur during the dry spell may be determined so that the retention capacities of the surface depressions present at the start of the rainfall are known. During periods of rainfall the balance calculation is carried out neglecting evaporation losses. If precipitation begins when depressions are still partly filled, the QQS program applies the degree of filling in order to calculate the initial or starting losses.

Evaporation rates during dry-weather periods are computed as a function of temperature and time. The temperature is interpolated according to the day time from monthly maximum and minimum temperature values incorporated in the input data. The temperature-evaporation relationship itself also is specified as associated values by input. This is a simplified way of considering evaporation but is adequate for long-term simulations.

Quantity of Dry-Weather Flow--

For combined sewer systems, the storm runoff must be added to the dry-weather flow originating from domestic, commercial, and industrial sources, and possibly from additional inputs such as ground water infiltration and construction site water. The domestic dry-weather flow portion is calculated in accordance with the number of residents and the average per capita water consumption rate. Defining the per capita consumption rate losses resulting from sprinkling or leaks must be excluded. The calculated domestic flow is enlarged by an allowance to account for smaller commercial water use to which possible additional inputs are added. This total value may be additionally adjusted by a factor, called water consumption factor, for each drainage area. The industrial sewage of major water users may be accounted for also seperately for each drainage area.

Because the dry-weather flow rate is subject to considerable variation during the course of a day, a variable diurnal dry-weather flow pattern may be used. By applying an estimating factor, it is possible to change all dry-weather flow input linearly by altering one single value, which can prove helpful if various water consumption levels are to be quickly examined.

Runoff Quality

Quality of Storm Runoff--

During a rainfall, part or all of the pollution constituents present on runoff surfaces are washed off. This process is thought to be controlled mainly by rainfall intensity, rainfall duration and usage of the surfaces, which varies with time of day (e. g. intensity of street traffic). These influences are nonlinear. In order to be able to formulate the relations mathematically, a new calculation concept was developed based on the Unit Hydrograph method. The convolution integral - Equation (1) - for the calculation of storm runoff quantity was extended by nonlinear functions which represent the effects of rainfall duration and diurnal variation in the process of

pollution wash-off. If the pollutant unit impulse response, $\Phi(t-\tau)$, is known, then the pollution load P(t) washed off is as follows:

$$P(t) = \int_0^t RDI(t)\ DTI(d)\ \Phi(t-\tau)\ I_{eff}(\tau)\ d\tau \qquad (5)$$

where
- d = time of day
- DTI(d) = function of diurnal variation of pollutant wash-off due to land use
- RDI(t) = function for decrease of pollutant wash-off with increasing rainfall duration.

DTI(d) and RDI(t) are dimensionless functions. The relations between the time variables t, τ and d are illustrated in Figure 4. The diurnal variation factor usually varies between 0.7 and 1.0, but may be kept at 1.0 until the modeler develops expertise to vary this parameter. Individual diurnal variation functions may be inserted to describe the wash-off of any of the pollution parameters. The rainfall duration factor starts at 1.0 at the beginning of a rainfall and is normally decreased to a minimum value of 0.2 within one hour. Individual rainfall duration functions, RDI(t), may be used for any of the four land use types described above and for any of the pollution parameters to be described, thus characterizing the wash-off behaviour of different land use types and pollutants.

The wash-off behaviour discussed above may be adapted for all conservative pollutants such as total suspended solids, settleable solids or metals. If it can be assumed that the change of BOD_5, COD or fecal coliform values with time can be neglected for the usually short periods of storm events, these parameters may also be simulated with the method for conservative pollutants.

Balance for Pollution Build-up and Wash-off--

During dry-weather periods, pollutants accumulate on the surfaces. The effect of the dry-weather period on the magnitude of the pollution $P_{up}(z)$ which is present in the drainage area at the time of the beginning of a rainfall is approximated by the following pollution build-up function:

$$P_{up}(z) = \left(1 - \frac{c_1 z + 1}{c_2 z^3 + c_3 z^2 + 1} \right) P_{up,100} \qquad (6)$$

where
- z = number of time steps (of 5 minutes) and
- $P_{up}(z)$ = pollution accumulated after z time steps.

The form of the above semi-empirical function is based on the results of various sampling programs (2 and 11). The magnitudes of the coefficients c_1, c_2 and c_3 are in the range of 10^{-4} to 10^{-7} and depend on the pollution parameter examined. In addition, these coefficients may be supplied separately for different land use types. The maximum pollution build-up,

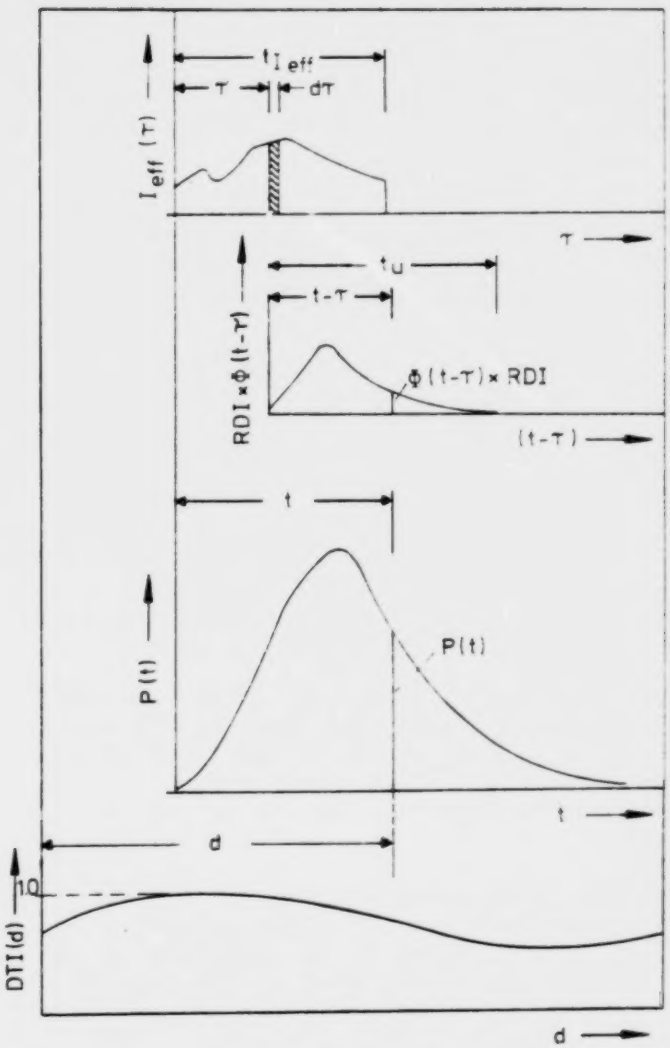

Figure 4. Relation between t,τ and d for wash-off calculation

$P_{up,100}$, varies with respect to the time of the year; and is therefore controlled by an additional, dimensionless function, which may be different for the individual pollution parameters but whose numerical values vary from 0.5 to 1.0. The maximum pollution values may be entered individually for each pollution parameter and separately for different land use types.

Total pollutant loads washed off during heavy storms that have been observed in sampling programs give an indication of maximum pollution build-up. Table 3 gives reference values for various pollution parameters based on present experience. It should be understood that the values vary from case to case and depend on land use type and other factors.

The mutual influence of pollution build-up and wash-off is mathematically formulated by a balance calculation. This balance includes the periodic removal of pollutants by street cleaning. The street cleaning influence is quantified by defining frequency and cleaning efficacy individually for each land use type. Thus, the amount of pollution present at the beginning of rainfall in all drainage areas is established.

TABLE 3. REFERENCE VALUES FOR MAXIMUM POLLUTION BUILD-UP

Pollution parameter	$P_{up,100}$
BOD_5	15 to 40 kg/ha
$KMnO_4$	100 to 200 kg/ha
COD	100 to 200 kg/ha
Settleable solids	60 to 80 kg/ha
TSS	60 to 125 kg/ha
Lead	up to approx. 0.03 kg/ha
Total phosphorus	up to approx. 0.2 kg/ha
Fecal coliforms	5×10^{12} to 50×10^{12}/ha

Quality of Dry-Weather Flow--

Analogous to the computation of combined flows in the case of combined sewer systems, the pollution load of the storm runoff is superimposed on the pollution originating from domestic, commercial, and industrial dry-weather flow. The pollution values are entered as concentration values individually for the parameters investigated for domestic (including commercial) sewage. Because here quality may also be subject to diurnal variation, a variable diurnal concentration pattern may be used for each of the parameters investigated. For industrial sewage individual constant concentrations may be specified for each drainage area. This allows for special consideration of wastewaters from particular industries.

SEWER SYSTEM ROUTING

Flow Routing in the Sewer System

The storm-runoff hydrographs determined for the drainage areas and the drainage area dry-weather flows are, after superposition, transferred to the nodes of the sewer system. However, nonlinear input-response behaviour must be adopted for the major sewer system because of storage and backwater ef-

fects and because of the controlling effects from diversions, overflows, and detention structures. Thus, a hydrodynamic calculation method, based on the continuity and energy equations, is applied in sewer network flow simulation, as opposed to the hydrological method used for drainage area runoff determination. It is this hydrodynamic approach that makes it possible to model diversion structures, detention basins, overflow chambers, pumping stations and operational control gates according to their actual hydraulic performance.

The configuration of a sewer system prepared for calculation purposes consists of a number of pipe elements (sewers) connecting the system nodes. The logic of the system is based on these nodes. The different node types considered in the QQS program are shown in Figure 5. The basic node (Figure 5-a) may have one to three inflows from sewers, one to three inflows from drainage areas, and one or two outflows, thus allowing for simulation of junctions and diversions. Overflow (Figure 5-b) and basins (Figure 5-c and d) allow for one to three inflows from sewers and one to three inflows from drainage areas as well, but for only one outgoing sewer. Gates for operational control (Figure 5-e) may be located in either one of the outflowing branches of a diversion or in the outgoing sewer of an overflow. Because almost any sequence of sewers and nodes is allowed, the simulation of existing sewer systems can normally be accommodated.

The hydrodynamic calculations are based upon the two partial differential equations which describe an unsteady, non-uniform, frictional flow regime. The energy equation is

$$S_f = S_o - \frac{\partial H}{\partial x} + \frac{\partial}{\partial x}\left(\frac{v^2}{2g}\right) + \frac{1}{g}\frac{\partial v}{\partial t} \qquad (7)$$

and the continuity equation is

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \qquad (8)$$

where
- A = flow area
- g = acceleration of gravity
- H = flow depth
- Q = flow rate
- S_f = friction slopes
- S_o = invert slope
- t = time
- x = coordinate

The acceleration terms $\frac{1}{g}\frac{\partial v}{\partial t} + \frac{\partial}{\partial x}\left(\frac{v^2}{2g}\right)$ are omitted from Equation (7); however, the variation of the velocity head, $\frac{\partial}{\partial x}\left(\frac{v^2}{2g}\right)$ is retained as a re-

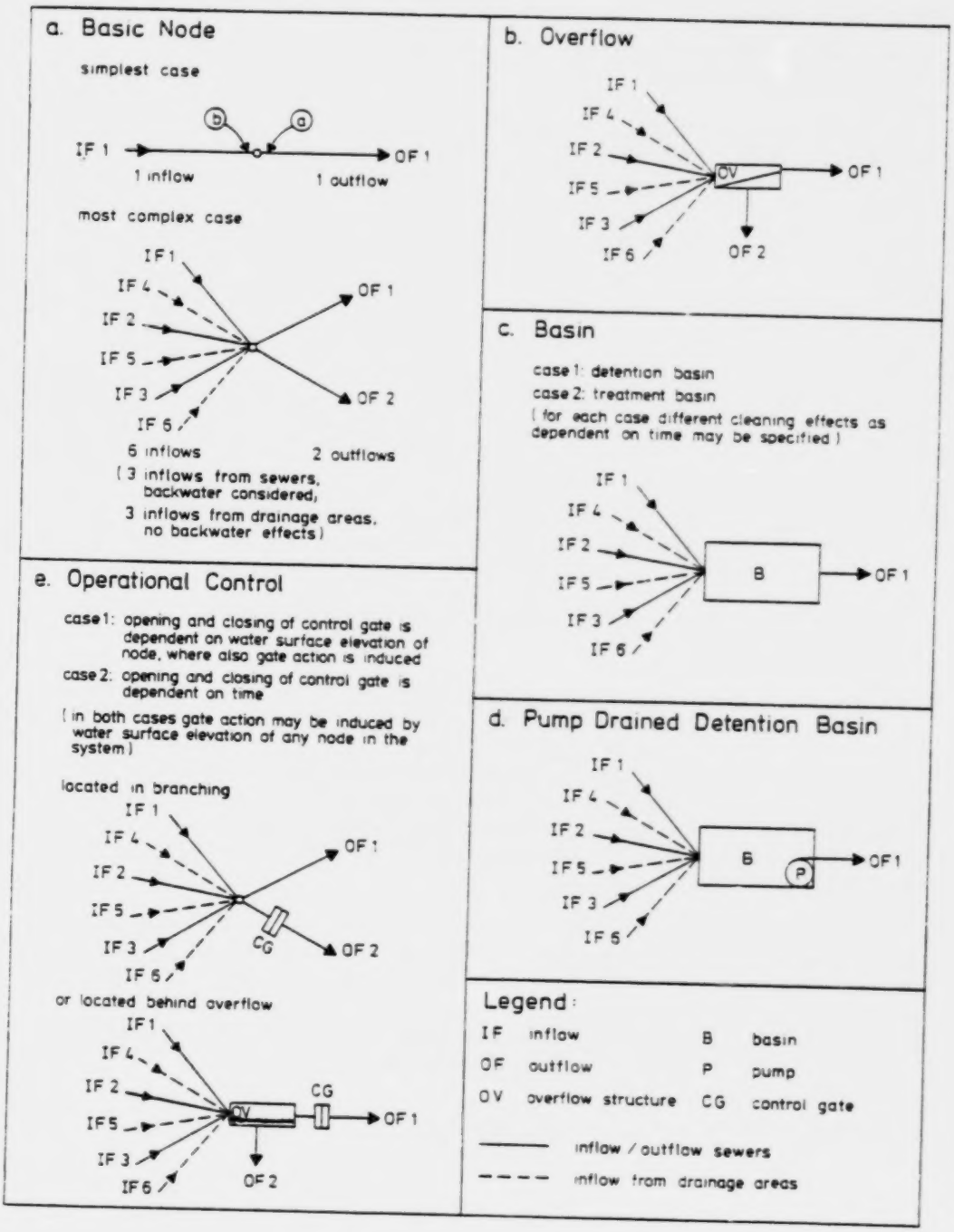

Figure 5. Different types of system nodes considered in the QQS program.

striction in Equation (12), below, by means of the unequal sign so that in fact only the acceleration component, $\frac{1}{g}\frac{\partial v}{\partial t}$, is neglected. These simplifications contribute to computer time savings, an important consideration in long-term simulations.

With these mathematical simplifications and after transformation into a difference form, Equations (7) and (8) may be expressed as follows (see Figure 6):

$$H_b - H_a = Y_a - Y_b - S_f \Delta x \tag{9}$$

$$\Delta H = (S_o - S_f) \Delta x \tag{9a}$$

$$\frac{Q_{a,1} + Q_{a,2}}{2} \Delta t + \frac{A_{a,1} + A_{b,1}}{2} \Delta x$$

$$= \frac{Q_{b,1} + Q_{b,2}}{2} \Delta t + \frac{A_{a,2} + A_{b,2}}{2} \Delta x \tag{10}$$

Equation (10) is but one of several ways that Equation (8) can be written in a difference form.

Equations (9) and (10) describe the flow behaviour in a sewer element. This set of equations has four unknown variables, i. e., the flow depths H_a and H_b and the flow rates Q_a and Q_b at the upper and lower ends of a flow element. Depth and flow values which have been determined for the preceding time step are used as starting figures for the iteration calculation of the time step in question. The sewer invert elevations Y, and thus the sewer slope S_o, are known. The cross-sectional area A is defined by its correlation with H and Q.

Equations (9) and (10) also provide the basis for the calculation of the friction slope in sewer elements. The friction slope S_f for a partially filled sewer element can be approximated by adopting a straight line water surface slope in the element and by setting the ratio of the mean calculated flow, $0.5 (Q_a + Q_b)$, to the uniform flow, Q_n, which corresponds to the mean wetted cross-sectional area of the element:

$$S_f = \left(\frac{Q_a + Q_b}{2 Q_n} \right)^2 S_o \tag{11}$$

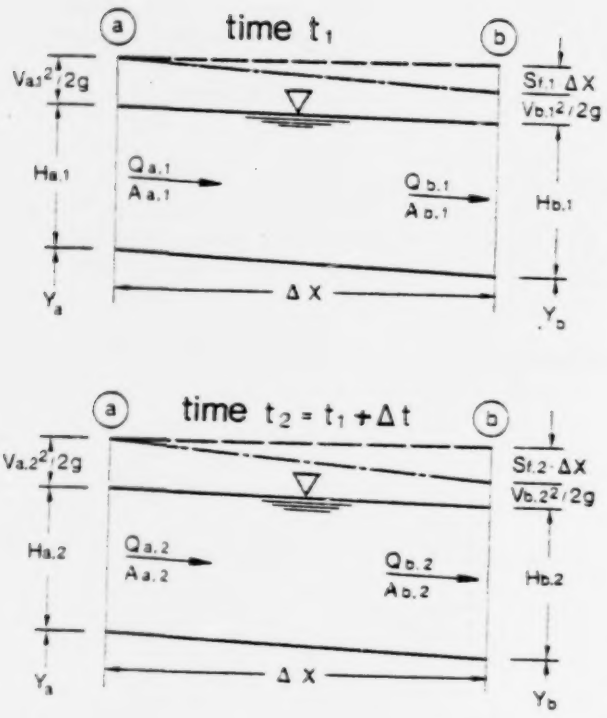

Figure 6. Difference equations as applied to a sewer element.

A further simplification is introduced by linearizing flow versus depth relations, with the actual sewer profiles being approximated by rectangular shapes of equivalent cross-sectional area and height. The friction slope equation then becomes:

$$S_f = \left[\frac{(Q_a + Q_b)\, H_v}{(H_a + H_b)\, Q_v} \right]^2 S_o \qquad (11a)$$

where Q_v = full flow capacity of sewer element
H_v = full height of actual (and equivalent rectangular) profile.

The full flow capacity of sewers, Q_v, is determined by means of the Manning formula or the Prandtl-Colebrook formula. Additional energy losses, such as those caused by manholes, bends, and roughness resulting from improper construction, age or incrustation, must be accounted for in the friction factors of those formulas.

Flow under pressure is also described by Equation (11a). In this case the cross-sectional area is the full profile area, and the water depth fig-

ures H_a and H_b are interpreted as pressure heights above the respective inverts. As opposed to the analysis of water hammer problems, compressibility of water and elasticity of pipe walls do not have to be accounted for because the pressure heads which may occur in sewer systems are of small magnitude.

Additional equations required for the determination of the four unknowns (H_a, H_b, Q_a, and Q_b) are provided by node and boundary conditions. The node conditions may be applied to as many as three inflowing elements and as many as two outflowing elements at a basic node, as shown in Figure 5-a.

The energy equation applied to a system node in its simplified form is as follows:

$$\sum_{i=1}^{i=3} \left(Y_{b,i} + H_{b,i} + \frac{v_{b,i}^2}{2g} \right) Q_{b,i} \geqq \sum_{i=1}^{i=2} \left(Y_{a,i} + H_{a,i} + \frac{v_{a,i}^2}{2g} \right) Q_{a,i} \qquad (12)$$

Production of negative water level differences at nodes is excluded by the backwater condition:

$$\min \left(Y_{b,i} + H_{b,i} \right) \geqq \max \left(Y_{a,i} + H_{a,i} \right) \qquad (13)$$

The continuity equation applied to a node is:

$$\sum_{i=1}^{i=3} Q_{c,i} + \sum_{i=1}^{i=3} Q_{b,i} = \sum_{i=1}^{i=2} Q_{a,i} \qquad (14)$$

where Q_c is the known inflow from a drainage area to a node during a given calculation interval. The inflow value, Q_c, includes storm runoff and sewage inflow from the drainage area. If the node is an overflow structure (Figure 5-b), Q_a also includes the overflowing quantity Q_o, which is defined by the Poleni formula:

$$Q_o = \frac{2}{3} \mu \, l \, h^{3/2} \sqrt{2g} \qquad (15)$$

where μ = overflow weir coefficient
l = weir length
h = water depth above weir crest.

Where a node represents a pump, Q_a (downstream from the node) is the maximum pumping rate possible for the prevailing pressure difference. However, if Q_b (upstream of the node) is less than the maximum pumping rate possible, Q_a equals Q_b. Pumping capacity is entered as a function of pumping head.

Boundary conditions for sewers at the upstream ends of a study area are either $Q_{a,i} = Q_{c,i}$, where $Q_{b,i} = 0$, or are $Q_{b,i}$ hydrographs contributed from upstream areas. Uniform flow conditions are assumed for the sewer sections at the downstream boundaries of the study area, with the flow depths calculated as

$$H_b = Q_b \cdot H_v/Q_v, \text{ where } H_b \leq H_v.$$

This system of equations takes the essential hydrodynamic features of sewer network flow into account. Filling and emptying of the sewer network is taken into account by the continuity equation - Equation (10) -, which is applied to every element. Acceleration and deceleration of flow are represented in Equation (9). In the case of deceleration, ΔH becomes positive ($S_f < S_o$) and in the case of acceleration, ΔH becomes negative ($S_f > S_o$). The effects of backwater exerted on neighboring elements are accounted for by Equation (13). For basins and overflow structures a horizontal invert and a horizontal water level are adopted, for which Equation (9) reduces to $\Delta H = 0$.

The system of equations given above is solved successively for each calculation interval, Δt. Because the system of equations has nonlinear elements, solution is accomplished by means of an iterative method applying mathematical convergence aids.

The iteration method, applied to every time step, follows a specific pattern. Unknown flows are determined in a downstream oriented calculation by inserting the flow depths or pressure heads of the preceding iteration in the equations. Then an upstream oriented calculation is carried out which applies the flow values just determined and thus computes the corresponding flow depths or pressure heads. However, in the case of overflows, only from the outgoing element OF1 (Figure 5-b) backwater is considered. The downstream calculation applies both energy and continuity equations. The upstream calculation makes use of the energy equation for flow under pressure, whereas for free-surface flow conditions only the continuity equation is used. For the downstream calculation both equations are introduced to the calculation process as a third degree polynomial which is solved using the Newton-Raphson method.

The downstream-upstream procedure is repeated until certain programmed accuracy requirements are fulfilled. At present the computer program contains the tolerance values listed in Table 4, which control continuation or interruption of the iteration procedure.

A limitation of the number of iterations per time step may be applied as part of the data input. If the system is not convergent the tolerances may not be reached prior to termination of the iteration procedure. Such a condition may originate for instance at branching points, when the transition to backwater conditions is reached within the iteration procedure of a time step. Note: The degree of precision of the calculation results depends not only on the tolerance values and the maximum number of iterations permitted, but also on the degree of skeletonization of the sewer system.

TABLE 4. TOLERANCE VALUES FOR ITERATION CONTROL

Type of element	Water level tolerance (mm)
Sewer elements	25
Sewer diversions	10^{-2}
Overflows	10^{-2}
Pumps	10^{-4}

Pollutant Routing in the Sewer System

The pollutographs determined for the drainage areas by superimposing storm runoff pollution and dry-weather flow pollution enter the main sewer system at the system nodes. Sewer system flows and flow velocities determined by means of the hydrodynamic relations already described provide the basis for the simulation of pollution transport in the network. The pollutant routing part of the QQS model was conceived as a generally applicable method which permits calculation of the transport of all conservative pollutants involved.

In an analogy to Equation (14), a continuity equation is applied to balance the pollutant loads at system nodes (refer to Figure 5):

$$\sum_{i=1}^{i=3} P_{c,i} + \sum_{i=1}^{i=3} P_{b,i} = \sum_{i=1}^{i=2} P_{a,i} \qquad (16)$$

where P_a = pollutant load in downstream element (upper end)
P_b = pollutant load in upstream element (lower end)
P_c = pollutant load from drainage areas.

A uniform distribution of pollutants throughout the sewer cross-sections is assumed. At diversions and overflow structures, the pollutant loads are divided according to the partition of the flows.

P_c is known from the drainage area runoff quality calculation. P_b is determined by moving the pollutant loads through the elements, using the flow velocities at the upper and lower ends of the sewers which have previously been calculated for every time step as the transporting velocities. The pollutant load which passes through the lower end of a sewer element or a basin during a time step is thus computed by Equation (17) (see Figure 7):

$$P_{b,1} = \left(\sum_{i=1}^{i=n} P_i \right) + P_{(n+1),1} \cdot \eta \qquad (17)$$

where $\eta = \dfrac{\xi_{n,2} - \xi_{(n+1),2}}{\xi_{n,2} - \Delta x}$ (17a)

in which $\xi_{n,2} = \xi_{n,1} + \Delta\xi_n$ and $\xi_{(n+1),2} = \xi_{(n+1),1} + \Delta\xi_{n+1}$. (17b)

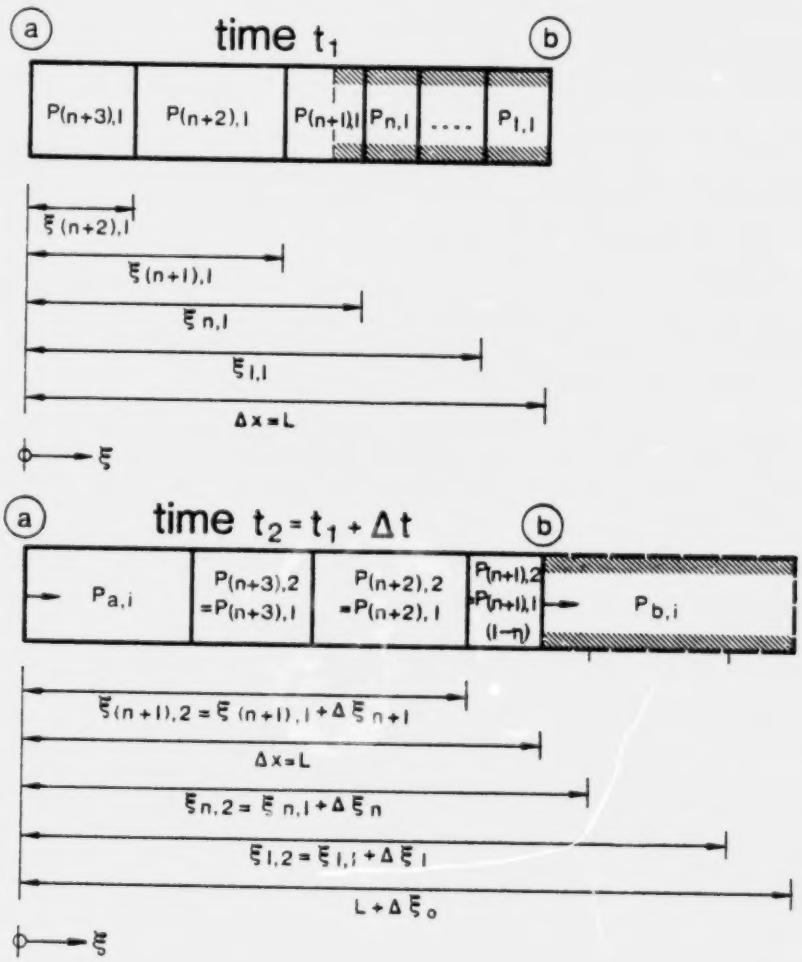

Figure 7. Travel paths of pollutant loads in an element.

Assuming that the flow velocity variation dv/dt in a sewer element is negligible, the flow path covered by the load during a calculation interval is:

$$\Delta\xi = \left(\xi + \frac{v_a \, \Delta x}{v_b - v_a} \right) \left(e^{\frac{\Delta t \, (v_b - v_a)}{\Delta x}} - 1 \right). \qquad (18)$$

Settling and scouring of sediments in the sewers of the simulated major system are not considered because the flow velocities in trunk sewers are assumed to be sufficiently large to preclude sedimentation. Settling and scouring occur mainly in lines at the extremities of systems and in lateral sewers. These effects may be accounted for in the pollution build-up and wash-off functions applied in calculations of drainage area runoff quality.

Pollution decay that occurs in detention structures is considered by including decay functions in the appropriate equations. Two different types of facilities may be accommodated, i. e., detention basins and storm or combined sewage treatment basins.

For either type of facility, individual decay functions may be assigned for any of the pollution parameters included. The decay function is entered as a variable function of the settling time, which is determined by the program using the flow velocity in the structure.

By means of these calculations, pollutographs are determined for every node of the sewer system. Taking pollutographs and hydrographs as a basis, associated concentration variations are computed for the pollution parameters in question.

RECEIVING WATER SYSTEM ROUTING

Flow Routing in the Receiving Water System

In QQS terms, the receiving water system represents a system separate from the sewer network. In the case of storm runoff or combined sewer overflow events, the receiving water system is computationally loaded by the storm discharges or combined sewer overflow quantities previously determined by the flow routing calculations for the sewer system. Nodal points of the receiving water system are the entry points of the stormwater outfalls or combined sewer overflow outlets, diversions, junctions, weirs, and invert drops.

The base flow of receiving waters is entered as a table of mean diurnal discharge values for the period simulated. These flows are superimposed on the loading inputs from the sewer system. The resulting flows are routed through the receiving water system in accordance with the same hydrodynamic principles that are applied in sewer system calculations. In this way, superposition of individual outfall or overflow quantities produces a loading configuration for the receiving water system throughout the study area.

Pollutant Routing in the Receiving Water System

Pollutant loads emanating from the sewer network are transferred to the receiving water system at the loading nodes and superimposed on the receiving water background pollution. This background pollution may be presented as functions of base flow rate and time of year. Changes in concentration such as those caused by an oxygen increase or decay and chemical reactions are not included as considerations in QQS. Because the flow path of receiving waters within a study area is normally of limited length and because the flow time is short compared with biochemical reaction times, it is assumed, within study area limits, that changes of water quality caused by biological or chemical effects are of negligible magnitude. Therefore, transport of pollutant loads through the receiving water system is calculated according to the same principles used in the pollutant routing calculation of the sewer system.

Superposition of individual pollutant loads from the sewer system produces overall pollutant loading configurations for the receiving water system for each pollution parameter investigated. These overall loadings computed by the QQS model may be used as the inputs to a simulation model of the entire receiving water to perform oxygen balance calculations.

STATISTICAL ANALYSIS

Analysis Possibilities

Continuous simulation deals with a multitude of events including rainfall as well as discharges and overflows from the sewer network that cause loadings of the receiving water system. All of these events may be characterized individually using various criteria such as durations, totals, mean values, etc. However, it would be prohibitive to examine and evaluate each and every individual event.

In order to obtain a clear picture of rainfall, runoff, overflow, and receiving water loading activity and to establish interrelations that may possibly exist, a statistical analysis of the fundamental variables must be performed. The results of such a statistical analysis should be presented first in the form of frequency distributions. A frequency distribution is developed by allocating the individual values of a variable to classes previously established. A class is defined by an upper and a lower limit, and only those values of the variable that remain within the range defined belong to that class. Each class contains a number of values which normally differs from the numbers for other classes, i. e., the individual classes have different frequencies, that form the frequency distribution.

If the frequency distribution is then integrated, a cumulative frequency curve is obtained. If a statistical evaluation is made of the results, which are related to the time span of the calculation interval (five minutes for the QQS program), the frequency can also be related to the dimension of time. In this case, the cumulative frequency curve is called a duration curve.

The cumulative frequency curve or duration curve shows how often or for how long a value is reached or exceeded, and for this reason is the most important and informative statistical curve that may be used to define discharge and overflow behavior. The relationship between the frequency distribution and the cumulative frequency or duration curve is shown schematically in Figure 8.

Beside the simple one-dimensional frequency distribution discussed above, the two-dimensional frequency distribution is also of practical importance. Two variables are examined together, with the intention of establishing a statistical relation between the variables (e. g., overflowing pollutant load in relation to receiving water flow). For example, critical combinations of receiving water loadings and base flows may be determined, in this way. For all individual events the two values of the variables considered are allocated to combined classes so that individual frequencies of value pairs are obtained for every combination of two classes. Because these classes have two dimensions, a frequency surface is obtained (Figure 9).

Because the numerical values of the variables examined may extend over wide ranges, it was necessary to include the possibility of using geometric or logarithmic values for classes. In addition, by input to the program the user can specify any desired class limits. The broad choice of class arrangements is also advantageous for handling the skewed frequency distributions that predominate in hydrological data because these distributions can thereby be made similar to symmetrical distributions, thus easing evaluation.

As a general principle, the class arrangements noted may be applied individually to every variable and, in the case of overflow and receiving water statistics, to every overflow node and every receiving water node. However, the classes may also be specified collectively for all nodes analyzed.

Statistical analyses may be done on an annual basis, or for several months (e. g., May through September), or for individual months.

Rainfall Statistics

As mentioned earlier, it is sufficient to simulate continuously the rainfall-runoff of a number of selected representative years rather than a complete long series of 20 years or so, in order to determine storm sewer discharge and combined sewer overflow behaviour of a drainage system and the subsequent water quality characteristics of a receiving water body. Therefore, to select a suitable time span for continuous runoff simulations, rainfall statistics may be examined within the scope of the QQS concept. Rainfall observations, which should extend over at least fifteen years, provide the basis for such statistical evaluation.

In most cases a sample of years can be found with basic rainfall characteristics that agree with those of the entire rainfall series available. A satisfactory conformity exists if the cumulative frequency curves or duration curves of the more important variables are identical, such variables for example, as rainfall duration, elapsed time to the interval with the ma-

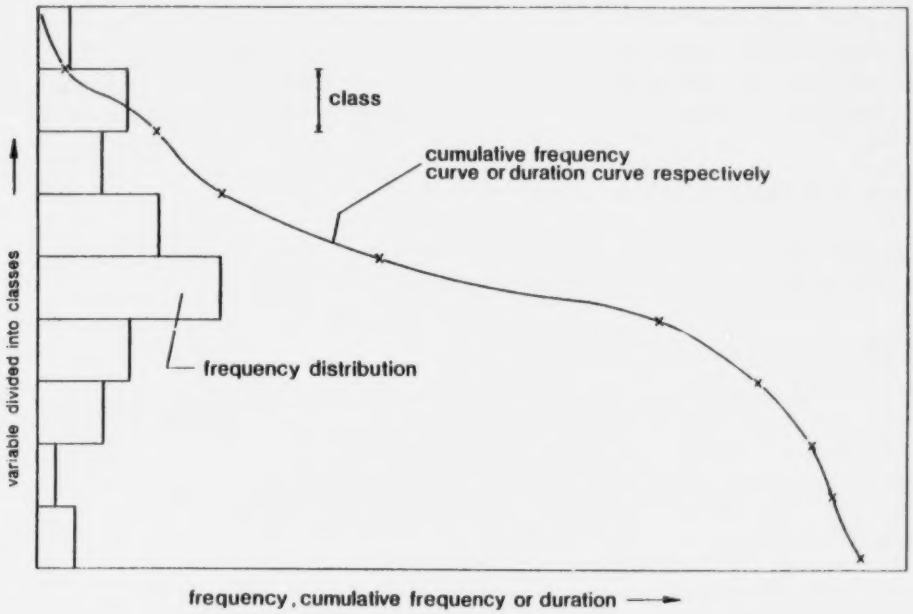

Figure 8. Relationship between the frequency distribution and the cumulative frequency or duration curve.

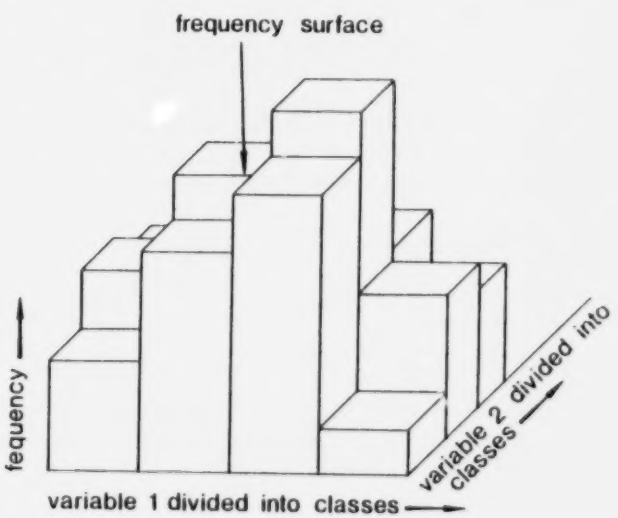

Figure 9. Frequency surface obtained from two-dimensional statistics.

ximum rainfall intensity, volume of rainfall, and mean intensity per rainfall.

In addition, the portions of storms occurring during the summer and winter season may be studied by means of a statistical evaluation of rainfall duration, volume of rainfall, and mean intensity per rainfall. Knowledge of these values helps in deciding whether, with respect to overflow behaviour, entire annual records have to be simulated or if simulation of the summer seasons would be sufficient.

Appendix 5 of Volume II, User's Manual, defines the variables that can be subjected to statistical analysis in the QQS program.

Discharge and Overflow Statistics

The stormwater outfall discharges and combined sewer overflow data for several years of record, as determined by way of a continuous simulation of a sewer system, form the basis for discharge and overflow statistics. Such data are compiled especially for overflow chambers, overflow weirs of detention basins, stormwater outlets, and outlets of detention structures operating under pressure.

Those variables which characterize the overflow events with respect to quantity as well as to quality and which can be subjected to statistical analysis are detailed in Volume II, User's Manual, Appendix 5. They total more than 100 variables or pairs of variables. Among these, the most important are overflow frequency and duration, storm discharges or combined sewer overflows, and pollutant loads and concentrations. As a general principle, all analysis possibilities described above may be applied to every variable and to every discharge or overflow node. In most cases, however, it is sufficient to examine only a small number of important characteristics in order to arrive at an assessment of discharge and overflow activity.

Apart from the statistical results, a number of single values may be derived for any time span desired (e. g., a given year or season) from the data used in the overflow statistics, such as

- total volume of water discharged to receiving water
- total pollutant loads discharged to receiving water
- maximum and mean concentrations of pollutants discharged to receiving water
- duration of longest overflow event.

Single values of this kind help in assessing the portions of the total annual pollution load which are conveyed respectively to the receiving water body and to the treatment plant.

Receiving Water Statistics

A loading characterization determined through a continuous receiving water simulation over several years provides the receiving water statistics. Evaluations are first carried out for all loading nodes, viz., the outlet

locations where stormwater discharges and combined sewer overflows enter the receiving water. The characteristics which can be statistically examined are listed in Appendix 5 of Volume II, User's Manual. These characteristics are evaluated for sewer system outlets (i. e., inflows to the receiving water) as well as for the receiving water cross-sections just upstream of loading nodes.

Variables related to total hydrograph duration, such as mean intensity of receiving water pollution or mean concentration, may also be statistically analyzed. These variables, however, have minor information value, because pollutant load variations tend to be damped and to level out in the water body.

All receiving water evaluations may be perfomed either taking into or leaving out of consideration the base values of receiving water flow and background pollution. The most important criteria for receiving water pollution assessment are the loading concentrations with their pertinent loading frequencies and durations.

SECTION 3

COMPUTER PROGRAM OVERVIEW

OVERALL COMPUTER PROGRAM DESCRIPTION

The following explanation of the computer program package pertinent to the QQS model concept is intended to provide condensed information on the program structure to the extent that appears to be necessary to understand Section 4 and 5 of this report. Detailed instructions about data input preparation, job control language, program error messages, and program output interpretation are given in Volume II, User's Manual.

The program package of the QQS model comprises of a number of individual programs: a data edit program, a sequence of three programs necessary to perform the actual runoff simulations, a program to print the runoff hydrographs and pollutographs in the case of single events, and a statistics program to evaluate continuous simulation results. In addition, there are two optional programs included in the package. The one simulates rainfall-runoff from individual catchments (not including major sewer routing), the other analyses precipitation data statistically. Figure 10 shows the sequence in which the individual programs are applied. An overall flow chart is provided in Figure 11.

The program DTCHCK checks the network quantity and quality data for format and plausibility. In case of errorless data (according to input specifications) the internal input files for the simulation part of the package are created.

The program DWTFLC simulates one full day under dry-weather flow conditions and establishes internal files (IF13 and IF21).

TXTFCE provides the headings for the output in English.

RCVRIN and MNTWKC perform the actual simulations of quantities and qualities of runoff from the catchments and their transport throughout the sewer network.

MNTWSP prints single event simulation results which were written by MNTWKC on an internal file (IF23).

For practical application of the QQS program package it has been found beneficial to treat the sewer network and the receiving water as separate systems, even though runoff and pollutant transport calculations in both systems employ the same principles. This separation permits the performance of data checks and simulations for verification or related purposes indivi-

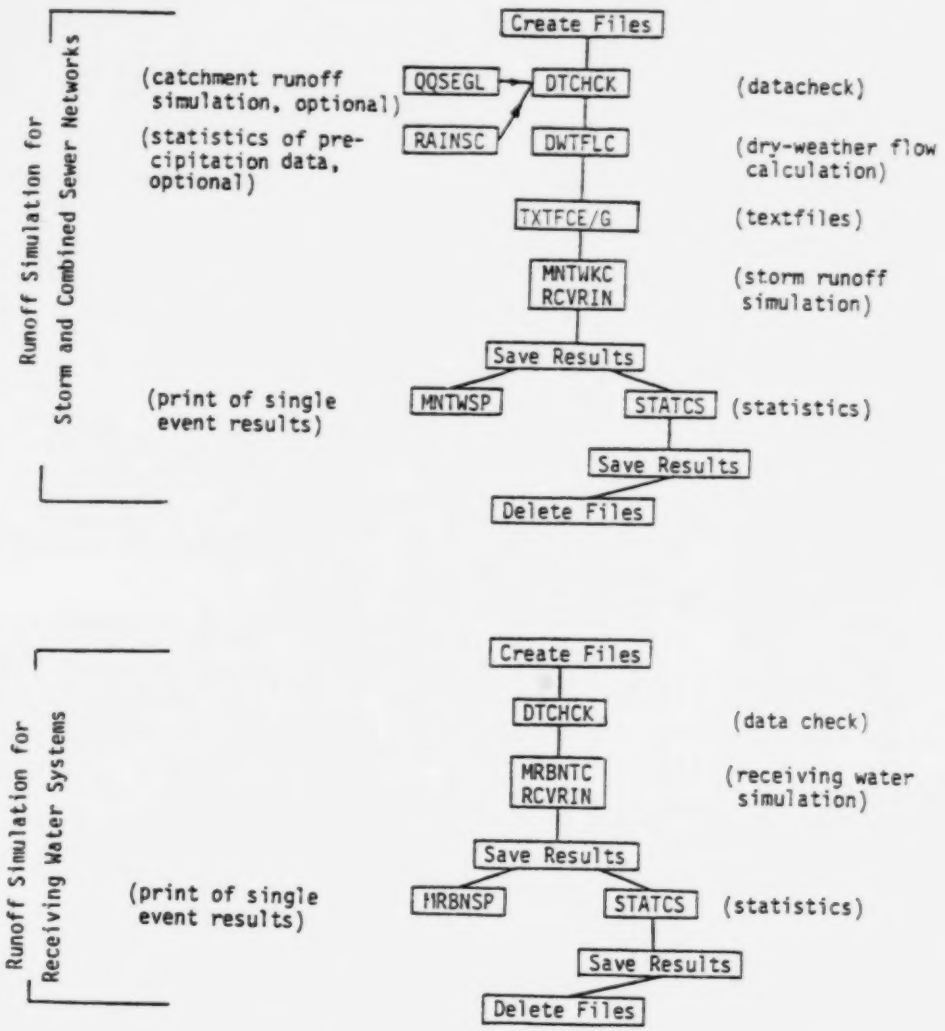

Figure 10. Runstream of the individual QQS programs.

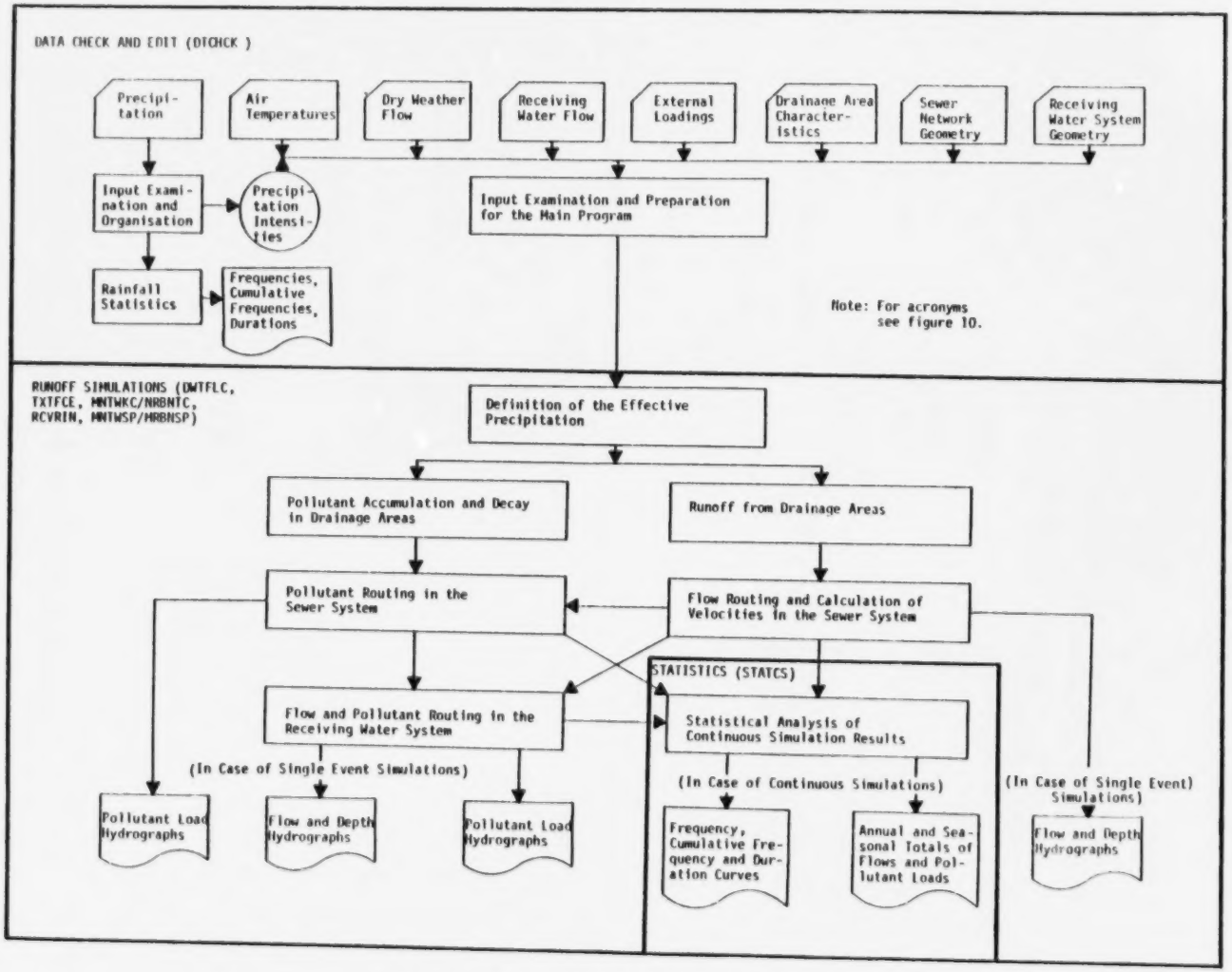
DATA CHECK AND EDIT (DTCHCK)
Precipi-tation
Air Temperatures
Dry Weather Flow
Receiving Water Flow
External Loadings
Drainage Area Character-istics
Sewer Network Geometry
Receiving Water System Geometry
Input Exami-nation and Organisation
Precipi-tation Intensi-ties
Input Examination and Preparation for the Main Program
Rainfall Statistics
Frequencies, Cumulative Frequencies, Durations
Note: For acronyms see figure 10.
RUNOFF SIMULATIONS (DWTFLC, TXTFCE, MNTWKC/NRBNTC, RCVRIN, MNTWSP/MRBNSP)
Definition of the Effective Precipitation
Pollutant Accumulation and Decay in Drainage Areas
Runoff from Drainage Areas
Pollutant Routing in the Sewer System
Flow Routing and Calculation of Velocities in the Sewer System
STATISTICS (STATCS)
Flow and Pollutant Routing in the Receiving Water System
Statistical Analysis of Continuous Simulation Results
(In Case of Single Event Simulations)
(In Case of Continuous Simulations)
(In Case of Single Event) Simulations)
Pollutant Load Hydrographs
Flow and Depth Hydrographs
Pollutant Load Hydrographs
Frequency, Cumulative Fre-quency and Dur-ation Curves
Annual and Sea-sonal Totals of Flows and Pol-lutant Loads
Flow and Depth Hydrographs

Figure 11. Overall flow chart.

dually for the sewer system or the receiving water system without handling the other system component simultaneously. Therefore, for the sewer system and receiving water system, individual program versions have been established which differ mainly in their capacity. These individual program versions also contribute to more economical computer use.

The pertinent program names for receiving water system routing are RCVRIN, MRBNTC and MRBNSP. Receiving water network routing can be started only after a corresponding sewer network simulation has been completed.

The results of continuous long-term simulations are stormwater discharges, combined sewer overflows, their pollution quantities, and receiving water loadings at specified nodes of interest. These data are organized and statistically evaluated in STATCS. One-dimensional and two-dimensional statistical analyses are performed for those properties and nodal points designated in the initial input instructions.

QQSEGL is a program which facilitates calibration and verification of drainage area calculations. This program simulates runoff and runoff quality from individual drainage areas and is an excerpt of the pertinent subroutines of MNTWKC. This program is included in the package but its use is optional.

The program RAINSC provides a statistical analysis of precipitation data and serves to select a suitable time span from longer rainfall observations for continuous rainfall-runoff simulations. This program is included in the package, but its use is optional.

The use of additional programs may prove beneficial, e. g., the HEC1 program for derivation of unit hydrographs (7), depending on individual project needs.

COMPUTER PROGRAM CAPACITY

The capacity of the QQS program system as described in this report is sufficient for normal applications of total service areas up to approximately 6,000 ha (15,000 acres) in size. At this approximate upper limit, with 100 drainage areas their average size would be 60 ha (150 acres). Considerable departures from these figures may be encountered in applications to diverse service areas. Regardless of the size of the total service area, three different rainfall records may be handled simultaneously in the simulations. Each of these records is ascribed to a fixed area by input. To a certain degree this will provide some consideration for nonuniformity in the distribution of precipitation.

Single event simulations can be made for a period of up to 24 hours. The time step is fixed at five minutes. Although it is desirable for the scope of urban runoff simulation to derive the pertinent input from records allowing for similar fine interpretation, it is still possible to interpolate the input data required in five-minute detail from less refined records. Single event simulations required for more than one day of data may be

performed by splitting the event and adjusting the initial conditions of successive runs.

Continuous simulations of up to 20 years, the time step being fixed at five minutes, are possible, but to save computing costs the selection of a 4 to 8 year period based on statistical analysis of precipitation criteria has been found to suffice without sacrificing reliability.

From one to four pollutants can be considered simultaneously in one simulation run. If necessary, additional pollutants may be handled in subsequent runs.

Either metric or English units can be used. The major data processing capabilities are summarized in Table 5. It should be noted that the program dimensions given are not rigid but may be adjusted by the programmer to accommodate larger areas and individual needs.

TABLE 5. DATA PROCESSING CAPABILITIES OF THE PROGRAM SYSTEM

Maxima		
Length of data for a single event simulation		24 hrs
Length of data for a continuous simulation		20 yrs
Statistical variables, total cases		118
Precipitation stations		3
Conservative pollutants		4
Area types (considering pervious and impervious separately)		4(8)
Receiving waters arbitrarily connected		2
Sewer network	- system elements	400
	- nodes	370
Drainage areas		100
Special structures	- overflows	35
	- basins and pumps	15
	- operational controls	20
External loadings	- constant	18
	- variable (only for single event simulation)	10
Receiving waters	- system elements	150
	- nodes	130
Specified nodes for statistical analyses	- special structures	50
	- arbitrary nodes	5

COMPUTER PROGRAM HANDLING

Computer Requirements

The complete QQS program package is written in Fortran IV and consists of approximately 30,000 statements. To date, the program package has been operated on UNIVAC 1108, UNIVAC 1110, DEC 2050 and AMDAHL 470 computers. However, the package can be used on all BATCH processing systems with Fortran IV compilers. A maximum usable core storage of 122 K-words (UNIVAC), which corresponds to 488 bytes, and a configuration with fast external mass storage are required.

Input Data

Input data are divided into four groups: precipitation, network and drainage area, quantity, and quality. All input may be provided in metric or English units, except for programs QQSEGL and RAINSC which only allow for metric input. Format requirements for all input data are provided in Section 3 of Volume II, User's Manual.

For continuous simulation, precipitation intensities must be supplied at 5-minute time intervals and dry spells between individual events must be specified. Gaps in precipitation records should be filled with suitable approximations. Control of measured precipitation records should be made by checking them against totalizer registrations. For single event simulations, precipitation data are entered with the network and drainage area data as part of their input.

Network and drainage area data consist mostly of geometrical data defining the sewer network or the receiving water system, logical connections of the individual elements, drainage area characteristics, and assignment of drainage areas to network nodes. Generally, these data may be derived from sewer network plans and aerial photographs.

Quantity data consist mainly of the data necessary to determine runoff quantities from drainage areas and dry-weather flows. Such data are unit flow hydrographs and data necessary to evaluate the effective precipitation, i. e., evaporation rates, initial or starting losses, and soil infiltration. Diurnal variation of dry weather flow, boundary flow conditions and receiving water flows are also specified in this group. These data are obtained from meteorological surveys, waterworks records, etc.

Quality data are analogous to the quantity data. They provide pollutant load unit graphs and their modifying functions, dry-weather flow quality, pollution in external loadings, and receiving water background pollution levels. Characteristic functions for pollutant accumulation and decay in the catchments, detention and purification in detention basins and treatment facilities, and data specifying intervals and efficiency of street cleaning are also contained in this group. Most of these data are derived from measurements and engineering experience documented in the literature.

In order to facilitate application of the program package and to avoid waste of computing time, the input data are checked by an extensive data-

edit program for errors and for plausibility. Such a data-edit is critical for an efficient and economical application of a comprehensive simulation model.

Output Data

The major single event simulation results are hydrographs and pollutographs, obtainable for any pipe element or any nodal point in the network. The output values are water surface elevations, flows, pollution loads and concentrations per time interval. Special outputs are given for structures like outfalls, overflows, detention facilities, pumping stations, and treatment facilities, providing information for all ingoing and outgoing conduits. For all outputs there is a choice of metric or English units. Output headings are in English.

In addition to hydrographs, and pollutographs, total runoff and total pollution loads washed from the study area are given for each simulation. Critical backwater conditions and their locations are indicated by a special output. Further, quantities and qualities of runoff from individual catchments may be handled and printed out separately by the program QQSEGL, a feature which has proved to save considerable time for catchment calibrations and verifications.

In principle, continuous simulation results are similar to those for single events, but the mass of information generated can be evaluated only by means of statistical analyses.

The major outputs are annual and monthly frequencies, cumulative frequencies, and durations of variables such as discharge and overflow volumes, peaks, averages, intensities, and associated pollution values. In all, 118 different cases of variables may be considered. One-dimensional statistical results are tabulated and graphed. Two-dimensional frequency distributions can be formed for any combination of variables specified in the input. From two-dimensional statistical results coincident frequencies and durations may be obtained. One may also easily check ranges of concurrence of hazardous conditions such as low receiving water flows and high overflow pollutant loads.

Further, annual and monthly totals and averages of discharges and overflow quantities and pollutant loads are given for the individual outfalls and overflows discharged to receiving waters, as well as their total impact on the receiving water. As for single event results, total runoff and total pollutant loads washed from the study area are provided over the time span simulated.

Output examples for single event and continuous simulation results are provided in Section 1 of Volume II, User's Manual.

SECTION 4

MODEL TESTING

HYPOTHETICAL TESTS

Battelle Pacific Northwest Laboratories evaluated several mathematical models that simulate time-varying runoff and water quality in storm and combined sewer systems. Quantitative and qualitative routing was tested simulating runoff through relatively simple hypothetical networks consisting of segments with different slopes and diameters. Included in this evaluation were some of the earliest tests made of the QQS program, the results of which have been reported in Appendix E of the pertinent report (1).

Hypothetical networks were also employed in the early stages of testing of the QQS program, to illustrate the plausibility of flow routing procedures used. The pipe reach for which runoff was simulated had a very flat slope of 0.05 percent and the entering hydrograph was for rapidly-varying rates of flow, conditions which are usually particularly challenging in mathematical modeling. Figure 12 shows the output flow hydrographs obtained at points 600 m, 1,200 m and 1,800 m downstream from the inlet point. The hydrographs are quite smooth and exhibit the expected damping effect.

COMPARISONS WITH MEASUREMENTS

Requirement for Measurements

Comparisons of measurements with results from simulations should be used to calibrate the model to a given study area and application. Some input functions such as unit hydrographs may be directly derived from suitable measurements made in the study area.

For derivation of input functions and model calibration, the following information is normally necessary:

- rainfall recordings of one or more stations;
- corresponding runoff measurements or water surface elevation recordings (and reliable calibration curves), synchronized with rainfall recordings;
- samples taken at sufficiently short time intervals during runoff for the pollutants considered;

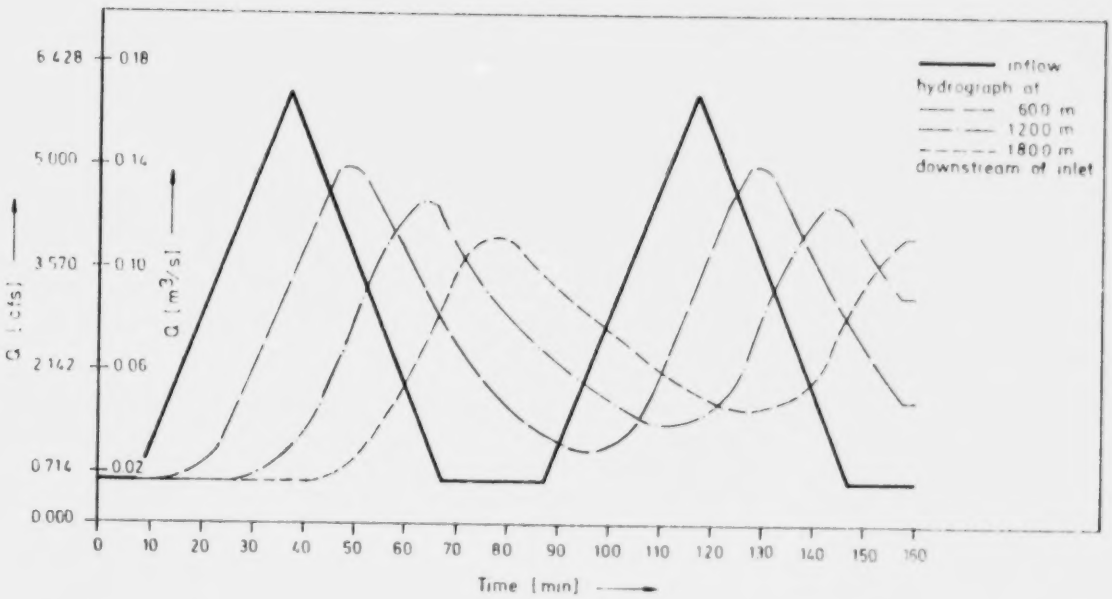

Figure 12. Hypothetical test of flow routing for a 0.61 m (2 ft) diameter pipe at a 0,05 % slope and with free inflow and outflow.

- indications of dry-weather flow quantity and quality prior to and after stormwater runoff; and
- time, duration and volume of preceding rainfall event(s).

A test catchment should be selected such that the boundary conditions allow for an unequivocal evaluation of the measurement. The following should be fulfilled:

- there should be no runoff entering the area under consideration from outside, unless it has been monitored;
- there should be no backwater effects within the test area caused by downstream influences;
- the rainfall station must be located within or close to the test area; and
- the characteristics of the test area should be representative of suitable portions of the study area.

In view of the intended comprehensive analysis of combined sewer overflow behavior, emphasis should be placed on the collection of data for storm events that cause relatively large overflows.

Comparisons of Different Catchments

A number of comparisons of QQS simulation results with field measurements have been performed. Table 6 includes only those comparisons for which complete sets of measurements were available. An extensive number of tests using incomplete sets of field measurements have also been performed.

In general, the necessary simulations were made using the program portion for drainage area runoff simulation only (QQSEGL). However, the simulation results for sites 8 and 31 in Rochester, N.Y., and for the seven miscellaneous locations in the sewer network of Vancouver, B.C., Canada, were taken from simulations using the programs DTCHCK, TXTFCE, MNTWKC, RCVRIN and MNTWSP (drainage area runoff and flow routing simulations).

All test areas and locations are described briefly below. Comparisons are shown in illustrations only if the calibration effort of the corresponding project had been completed at the time of writing, and if permission was obtained from the agencies, that made the measurements available, to publish the complete sets of comparisions performed.

For the comparison results presented, the input functions such as unit hydrographs and unit pollutographs are kept the same for all runoff simulations of a particular test area or network location. For each test area, the model was calibrated using all information available. Initial conditions are derived for each event to the extent that information on dry spells and preceding rainfall events could be obtained. Time synchronization of precipitation and runoff measurements frequently proved to be unreliable. Therefore, individual calculated hydrographs are shifted by up to two intervals (10 minutes) on some of the figures shown.

Augsburg Test Area

The test area of Baerenkeller in Augsburg, Germany, is mainly residential and is drained by a combined sewer system. Approximately one-fourth of the total area of 74 ha is impervious. The catchment houses 6,780 inhabitants, 3,750 of which leave the area during working hours. Railway tracks limit the test area to the north and south and to the west is another residential area. Flow measurements and samples that were specially taken for the pertinent QQS project, were gathered in a sewer line located at a ground surface drop representing the eastern boundary of the test area. All boundaries are clearly definable. Because of an appreciable ground surface drop and the resulting drop of the sewer line at that location, there are no backwater effects from downstream influences.

A meteorological station of the German weather bureau is located 1 km outside of the test area. All rainfall recordings used were obtained from this station. All runoff measurements were taken in a 1.0 m diameter manhole at the upstream end of the sewer line located below the ground surface drop. For this purpose, a side street was closed to through traffic for six months.

TABLE 6. COMPARISONS OF QQS SIMULATIONS WITH FIELD MEASUREMENTS FOR CASES WITH COMPLETE DATA

Location			Characteristic Data			Number of Comparisons Made								
Country	Municipality	Test Catchment	Area (ha)	Percent Impervious	Slope	Q	BOD_5	$KMnO_4$	COD	TSS	SS	PB	P	FC
Federal Republic of Germany	Augsburg	Baerenkeller	74.0	25	average	5	5				5			
	Stuttgart	Buesnau	31.7	37	av.-steep	5	4			4				
	Munich	Pullach	23.0	36	average	2	2			2				
	Munich	Harlaching	542.0	39	average	11	7			10				
	Munich	Ingolstaedter Strasse	96.0	37	flat	20	16			15				
	Munich	Josef-Wirth-Weg	33.0	16	flat	13	8			8				
Sweden	Gothenburg	Bergsjoen	15.4	40	average	11		5		5		6	6	
	Gothenburg	Torslanda	105.2	16	average	4			1	1				
USA	Rochester	North Street	33.6	31	flat-av.	3								
	Rochester	Dewey Avenue	28.7	37	flat-av.	2								
	Rochester	Colvin Street	77.5	41	flat-av.	2								
	Rochester	Site 8	390.0	61	flat-av.	2	2			2				2
	Rochester	Site 31	878.0	55	flat-av.	2	2			2				2
Canada	Vancouver	Alberta Street	73.8	42	average	7				1				
	Vancouver	Mackenzie Str.	26.6	25	average	11	3			3				1
	Vancouver	7 Diff. Network Locations	up to 672.0	17 to 95	flat-av. -steep	4								
	Toronto	Jones Avenue	45.0	50	average	4								
		Castlewood Ave.	27.0	50	average	4								

Water depths were recorded in the manhole and corresponding flows were defined by rating curves. Samples were drawn manually at the manhole for analysis of BOD_5 and settleable solids in time intervals of 5 to 10 minutes during storm events. This procedure was made possible by the fact that the field crew was based in a treatment plant located approximately 7 km from the sampling location. Once the crew anticipated a coming rainfall event, it could usually arrive at the sampling site prior to the start of runoff in the test area.

All samples taken were analyzed in the treatment plant laboratory for BOD_5 and settleable solids. Analyses were performed according to DEV guidelines (German standard methods for the examination of water, wastewater, and sludge). During the test period in the summer of 1974, flow was recorded and samples were taken and analyzed for approximately 20 rainfall events. The data from only five of these events were sufficiently complete to be used for model calibration purposes. Considering the difficult field conditions, this low yield was quite good. Because two of these five rainfalls had very low precipitation, emphasis was placed on the more intensive events of July 17, 1974, August 27, 1974, and September 25, 1974. Comparisons of the results for flow, BOD_5, and settleable solids are shown in Figure 13 for these three events.

Stuttgart Test Area

One of the first sets of comparisons between QQS simulations and field measurements was for five storm events monitored in the Buesnau test area of the Technical University of Stuttgart, Germany. This test area has a size of 32 ha, 38 percent of which is impervious, and a population of approximately 4,000 inhabitants. This catchment area is mainly residential with single homes and is drained by a combined system. The slope of the catchment ranges from flat to a slope of 6 percent. The steeper parts of the catchment, however, have no particular influence on surface runoff because individual properties are mostly limited by walls that cause steps in the surface. More details on this test area and on the data collecting system are contained in a report issued by the Technical University of Stuttgart (11).

Figures 14 and 15 show comparisons of QQS simulations with measurements for the storm events of September 19, 1967, March 15, 1968, May 17, 1968, and December 3, 1968, for flow, BOD_5, and total suspended solids. Figure 14 also shows the event of September 6, 1967, for which only the quantity of runoff is compared.

Munich Test Areas

In Munich, Germany, rainfall-runoff measurements were made and samples were collected in four test catchments of different sizes and characteristics. The metering stations of the Pullach and Harlaching test areas were installed and operated by the Technical University of Munich. The Ingolstaedter Strasse and Josef-Wirth-Weg stations were operated by the engineering department of the City of Munich. All measurements available from the four stations were used to calibrate QQS input functions for application

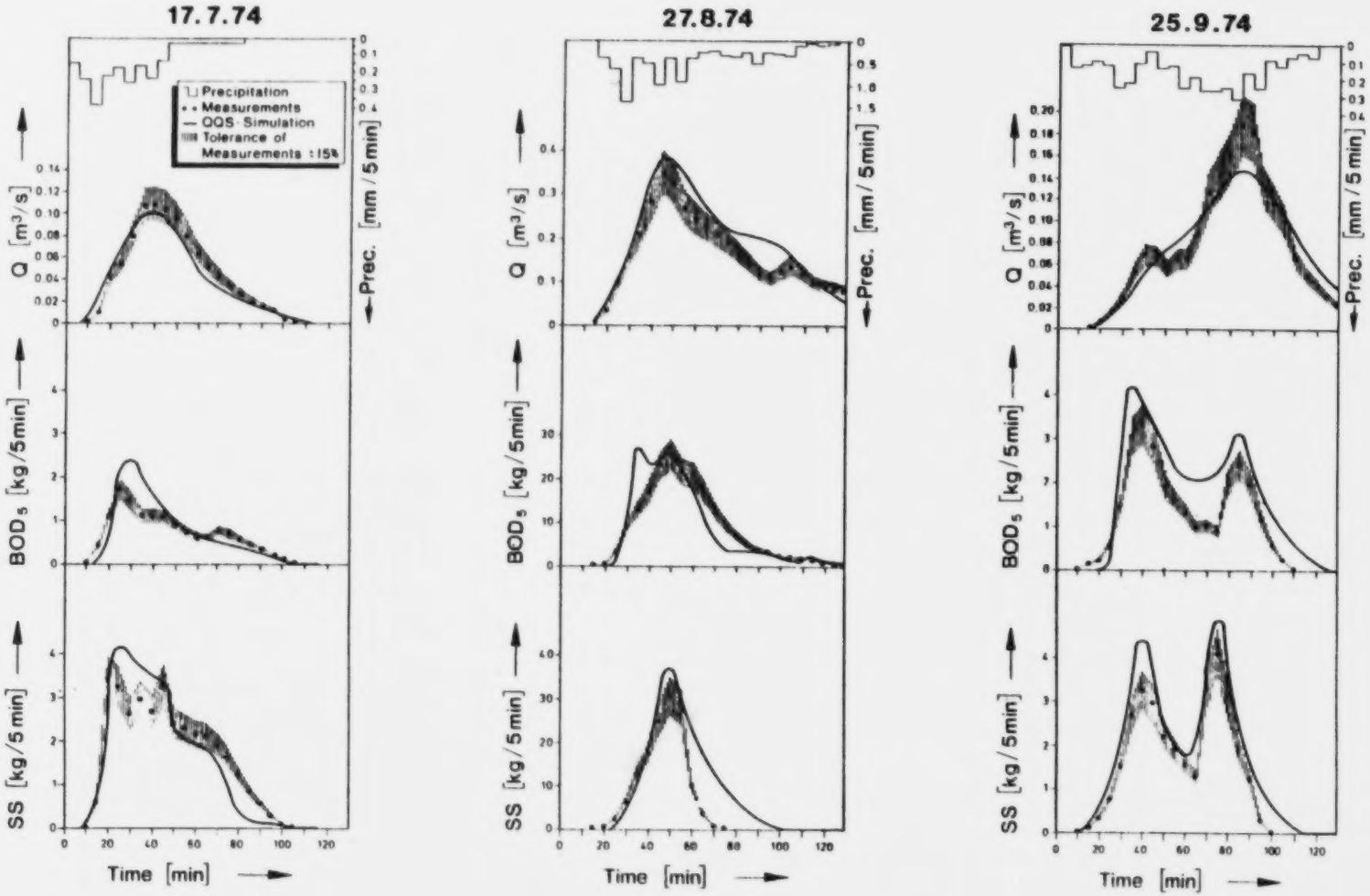

Figure 13. Comparisons with measurements; Baerenkeller (74 ha), Augsburg, Germany; storm events of July 17, August 27 and September 25, 1974.

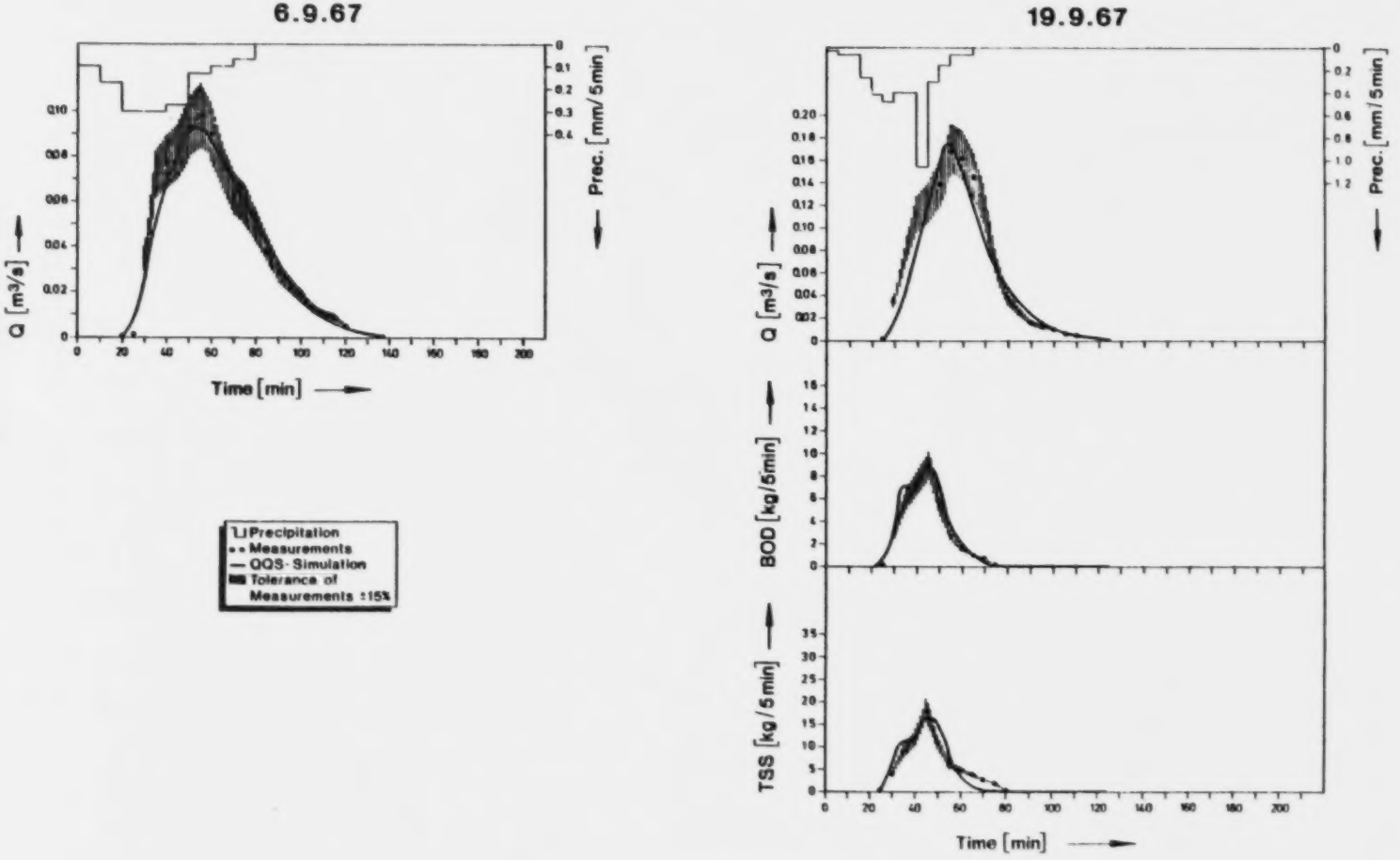

Figure 14. Comparisons with measurements; Buesnau (32 ha), Stuttgart, Germany; storm events of September 6 and 19, 1967.

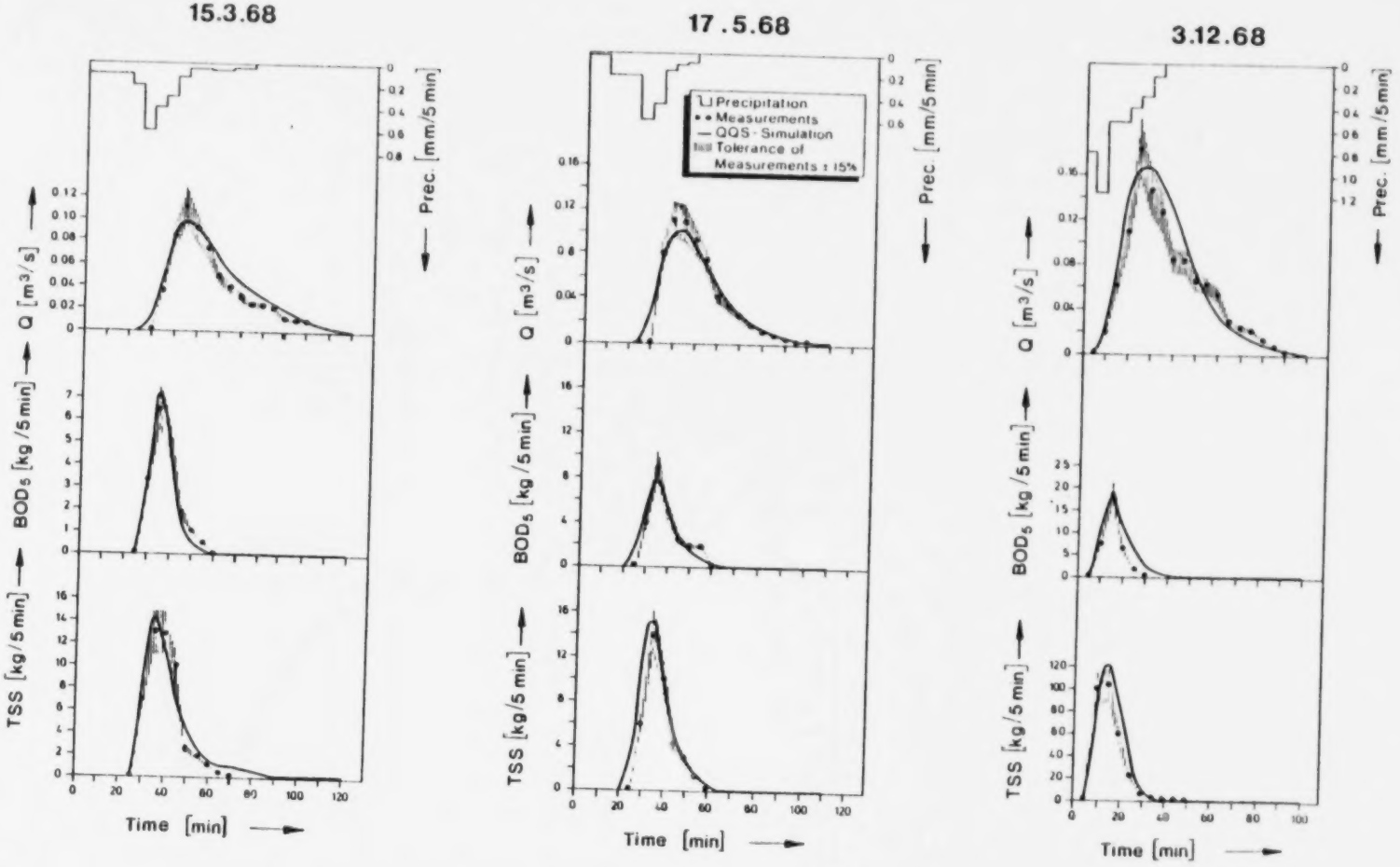

Figure 15. Comparisons with measurements; Buesnau (32 ha), Stuttgart, Germany; storm events of March 15, May 17 and December 3, 1968

in the overflow abatement study presently under way on the entire urbanized area of Munich.

The Pullach test catchment is 23 ha in size, of which 36 percent is impervious, and has an average slope. This single-dwelling residential area is drained by a separate storm sewer system. Catchment area and metering station features, sampling procedures and the data that have been collected have been reported and discussed (2). Complete information on flows, BOD_5 and settleable solids measured were made available for comparisons with QQS simulations.

Since the summer of 1976, precipitation, runoff, COD, some BOD_5, settleable solids, total suspended solids, and chemical data have been collected from the Harlaching test catchment. This mainly residential area has a size of 542 ha and is drained by a combined sewer system. Flow depths and some quality parameters are monitored continuously and water samples are drawn automatically. All collected data are checked and stored by data processing equipment. Some of the early measurements were provided for the calibration of the QQS model in connection with above-mentioned combined sewer overflow abatement study. The data collection effort is being continued.

The Ingolstaedter Strasse test catchment with an area of 96 ha and an imperviousness of 37 percent has a rather flat slope. The test area is drained by a combined sewer system. Land use is mainly residential and represents a mixture of older single homes and newer high-rise apartment buildings. In order to obtain clear boundary definitions for this test catchment, some sewers leading into the test area were cut off during the data collection period. A metering station was installed in an easily accessible area. Two manholes were constructed to contain the metering equipment. In both manholes, water depths were monitored whereby the measurements in the downstream manhole only served the purpose of checking for the occurrence of any possible backwater effects that might penetrate into the test catchment. The water quality samples were drawn in the upstream manhole. A calibrated metering weir was installed between the two manholes. One water depth recorder and the automatic sampler were stationed in a mobile shed that was parked over the upstream manhole. The second water depth recorder was installed in the downstream manhole. For the storm events of September 3, 14, 15 and 17, 1976, only runoff quantity measurements were available. In Figure 16, QQS simulations of runoff quantity have been compared with corresponding measurements. Figures 17 to 23 show comparisons for flow, BOD_5, and total suspended solids for the storm events of September 28 and 30, November 3 and December 2, 1976; and June 27 and 29, July 13, 19, 20, 25 and 31, August 1, 9 and 18, and September 4 and 9, 1977.

The fourth test area, monitored at Josef-Wirth-Weg, is a mostly single dwelling residential area that is partially industrial. It is 33 ha in size, has an imperviousness of 16 percent and a fairly flat slope. A peculiarity of this sewer system is that while street runoff and domestic sewage is discharged to sewers, roof and backyard runoff is infiltrated into the ground. The metering station was installed over an existing manhole just upstream of a pumping station and water depths were recorded and quality samples were

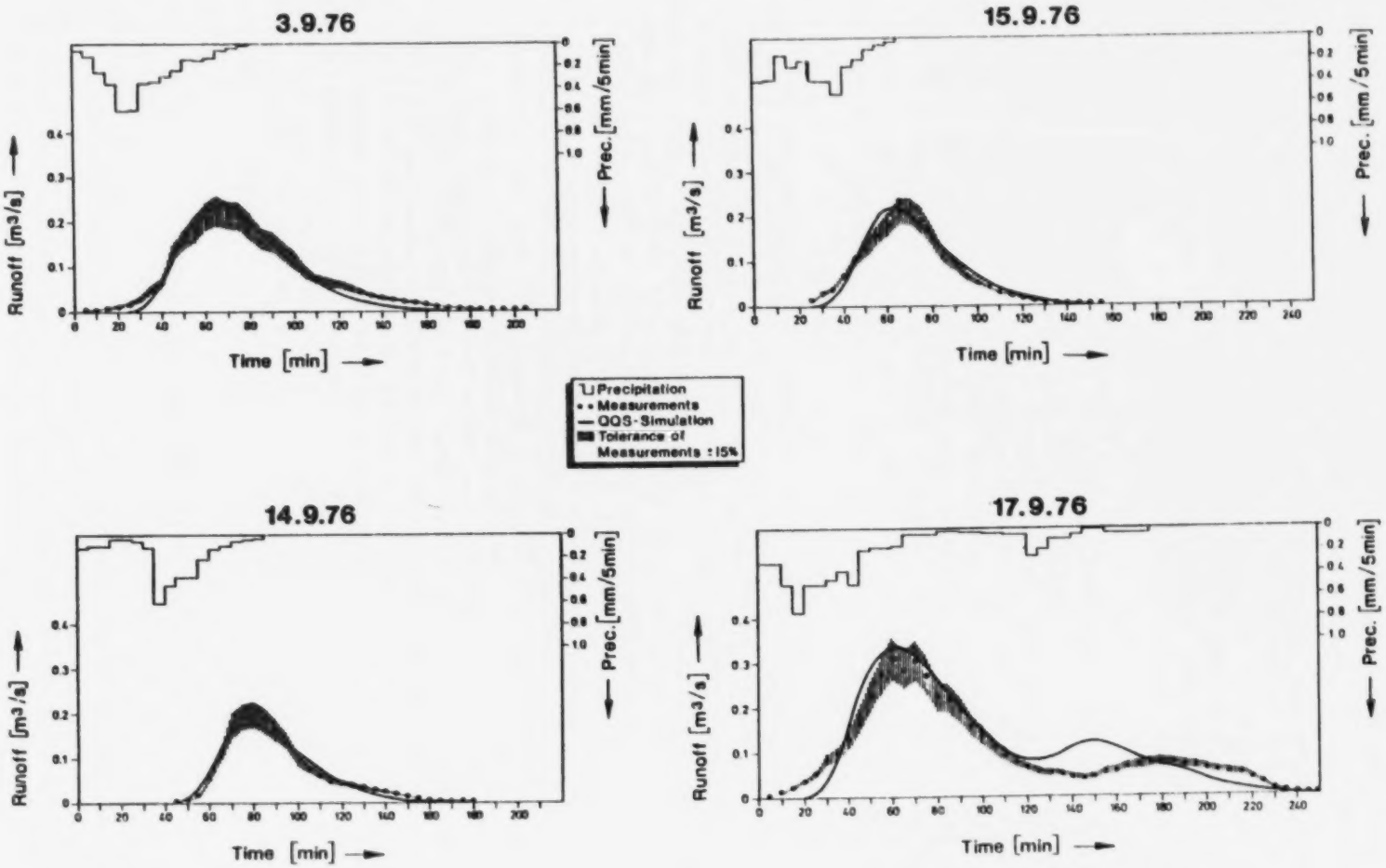

Figure 16. Comparisons with measurements; Ingolstaedter Strasse (96 ha), Munich, Germany; storm events of September 3, 14, 15 and 17, 1976.

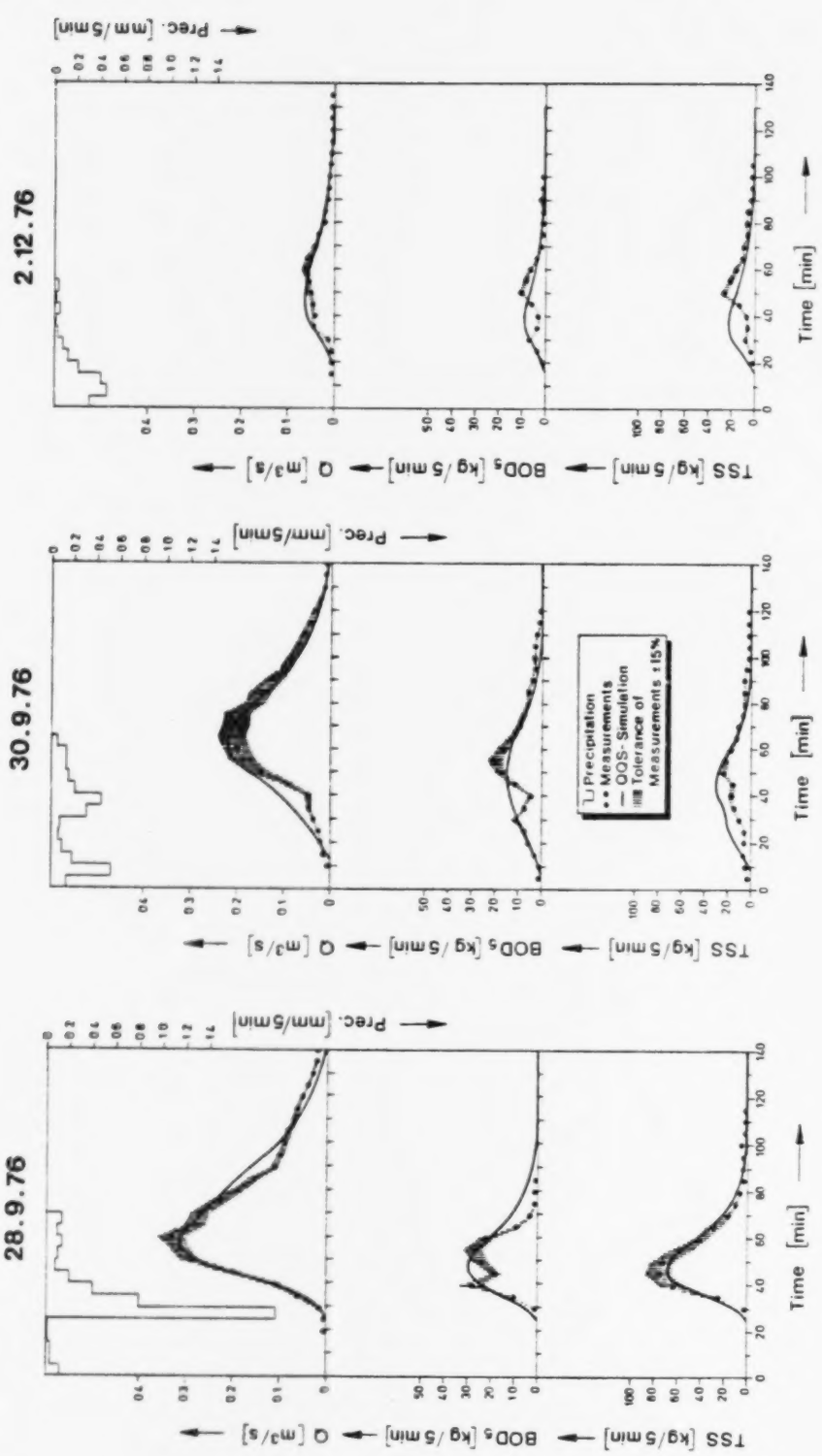

Figure 17. Comparisons with measurements; Ingolstaedter Strasse (96 ha), Munich, Germany; storm events of September 28 and 30, and December 2, 1976.

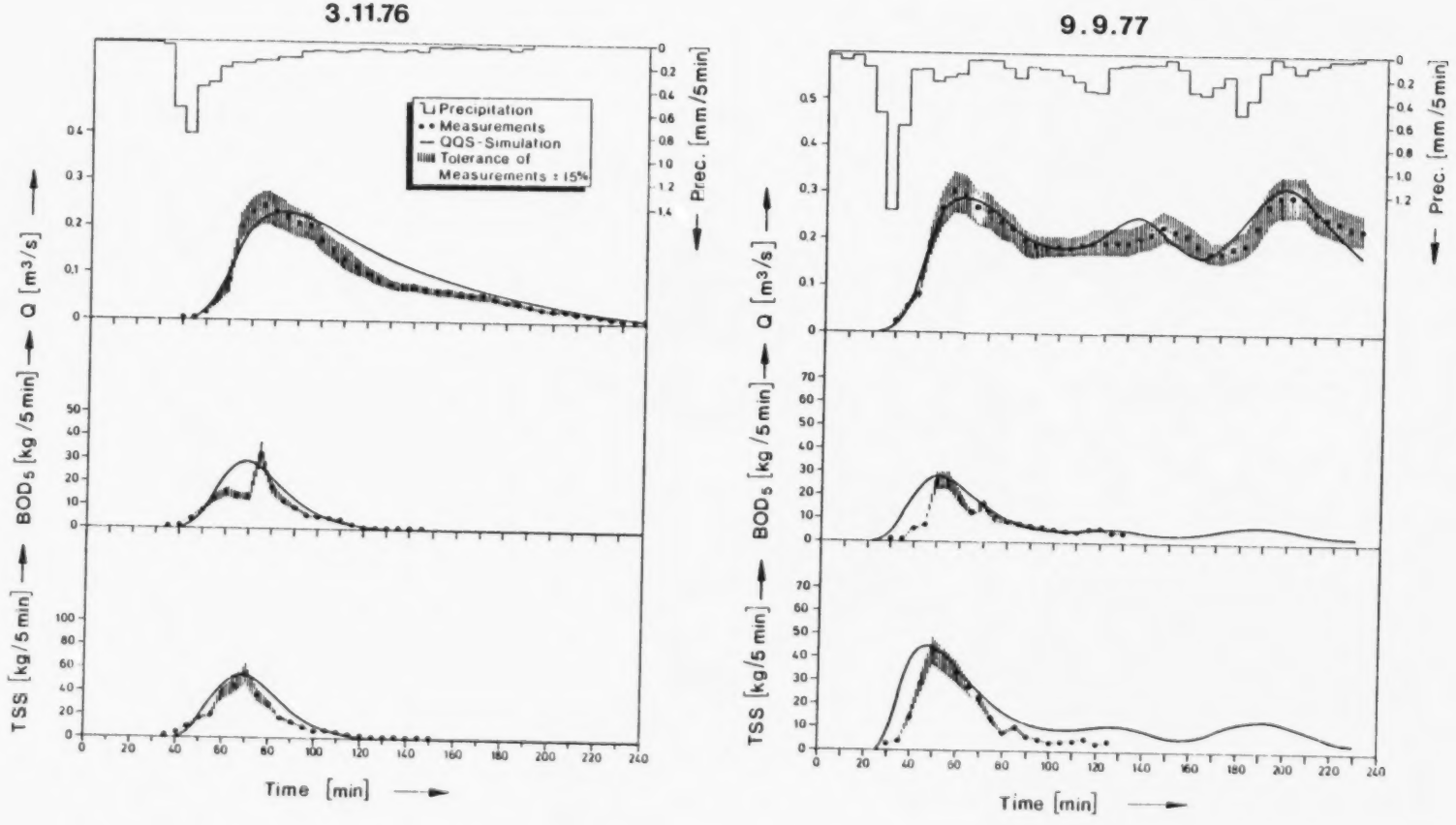

Figure 18. Comparisons with measurements; Ingolstaedter Strasse (96 ha), Munich, Germany; storm events of November 3, 1976 and September 9, 1977.

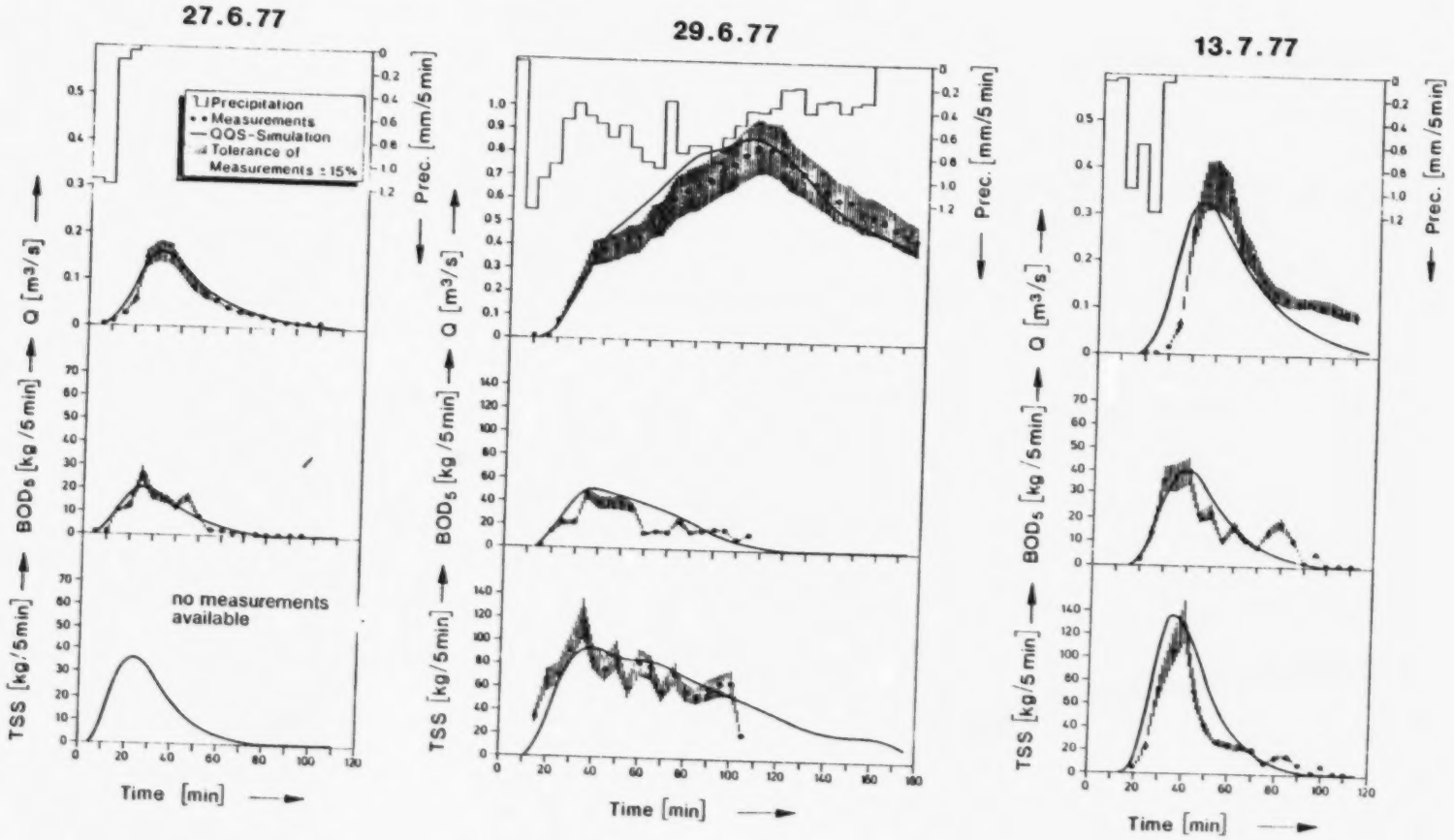

Figure 19. Comparisons with measurements; Ingolstaedter Strasse (96 ha), Munich, Germany; storm events of June 27 and 29 and July 13, 1977.

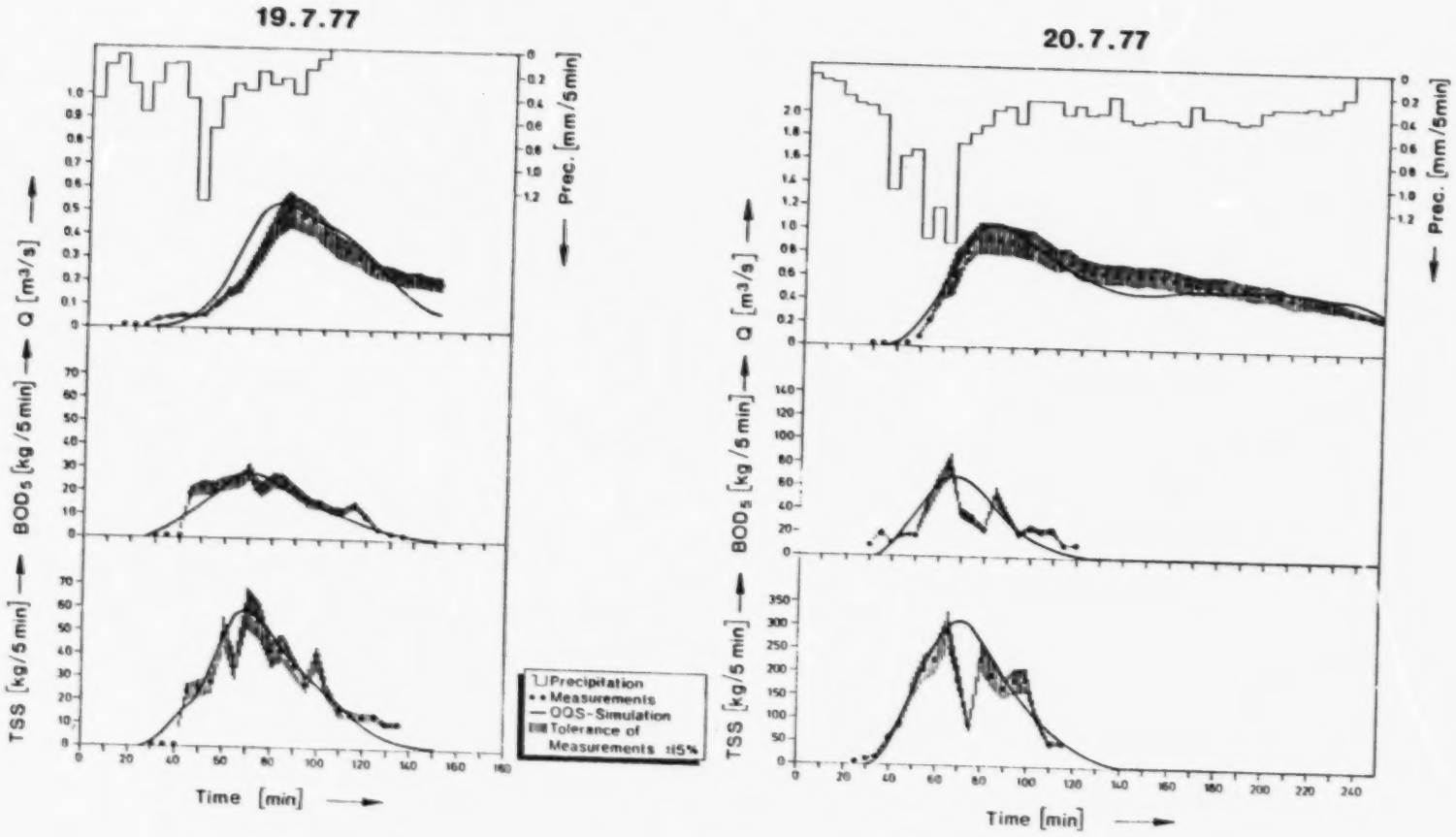

Figure 20. Comparisons with measurements; Ingolstaedter Strasse (96 ha), Munich, Germany; storm events of July 19 and 20, 1977.

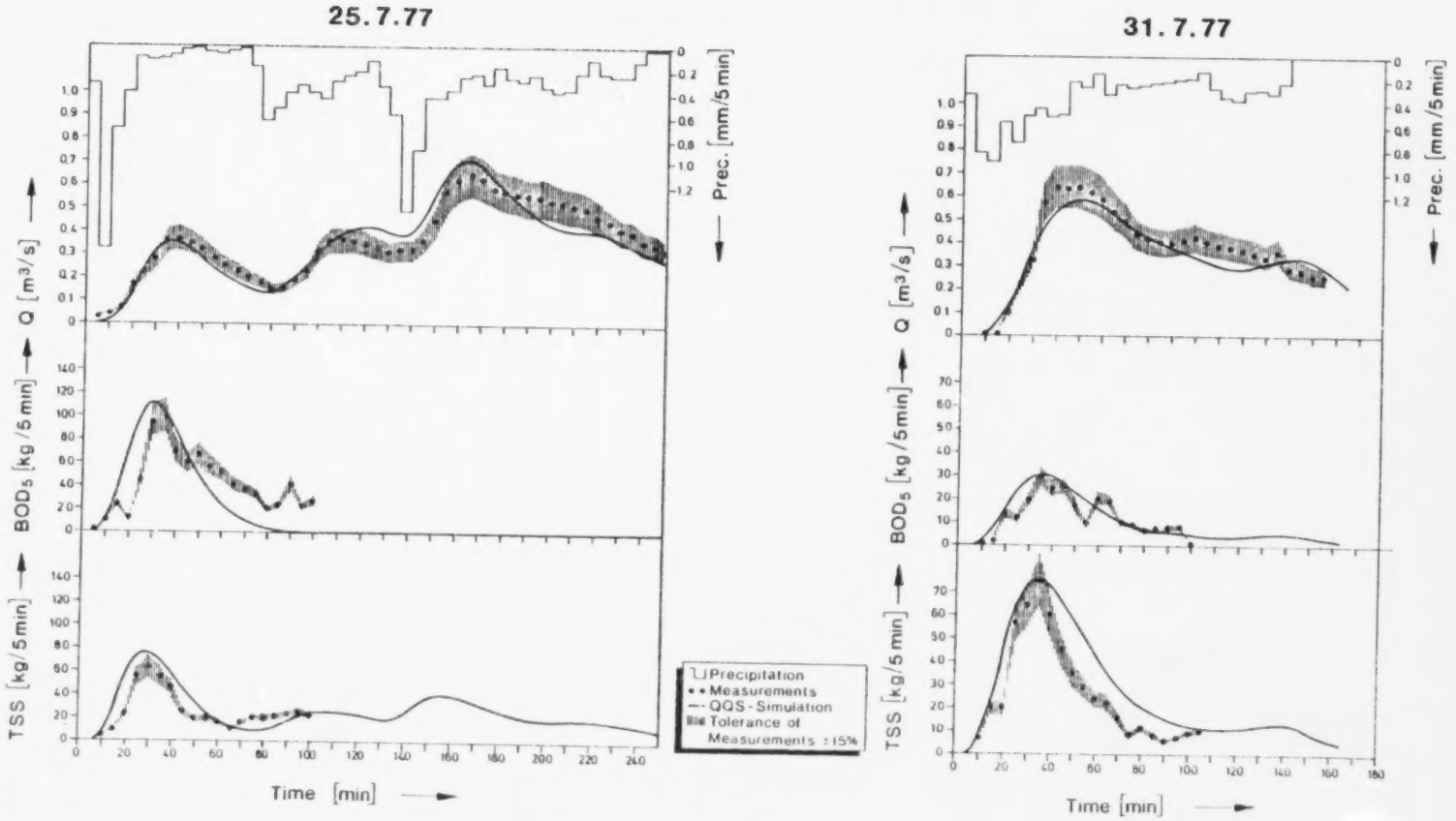

Figure 21. Comparisons with measurements; Ingolstaedter Strasse (96 ha), Munich, Germany; storm events of July 25 and 31, 1977.

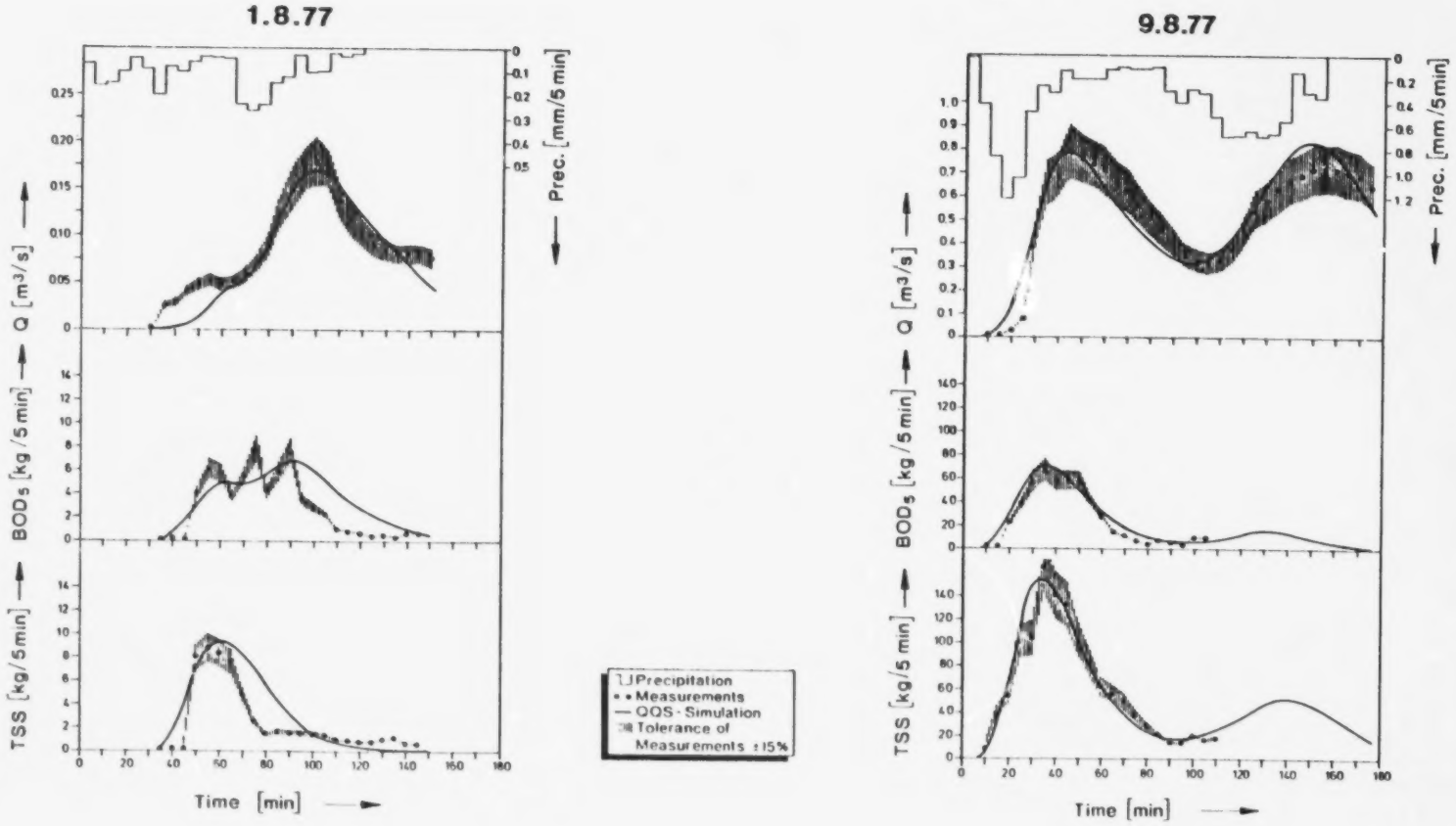

Figure 22. Comparisons with measurements; Ingolstaedter Strasse (96 ha), Munich, Germany; storm events of August 1 and 9, 1977.

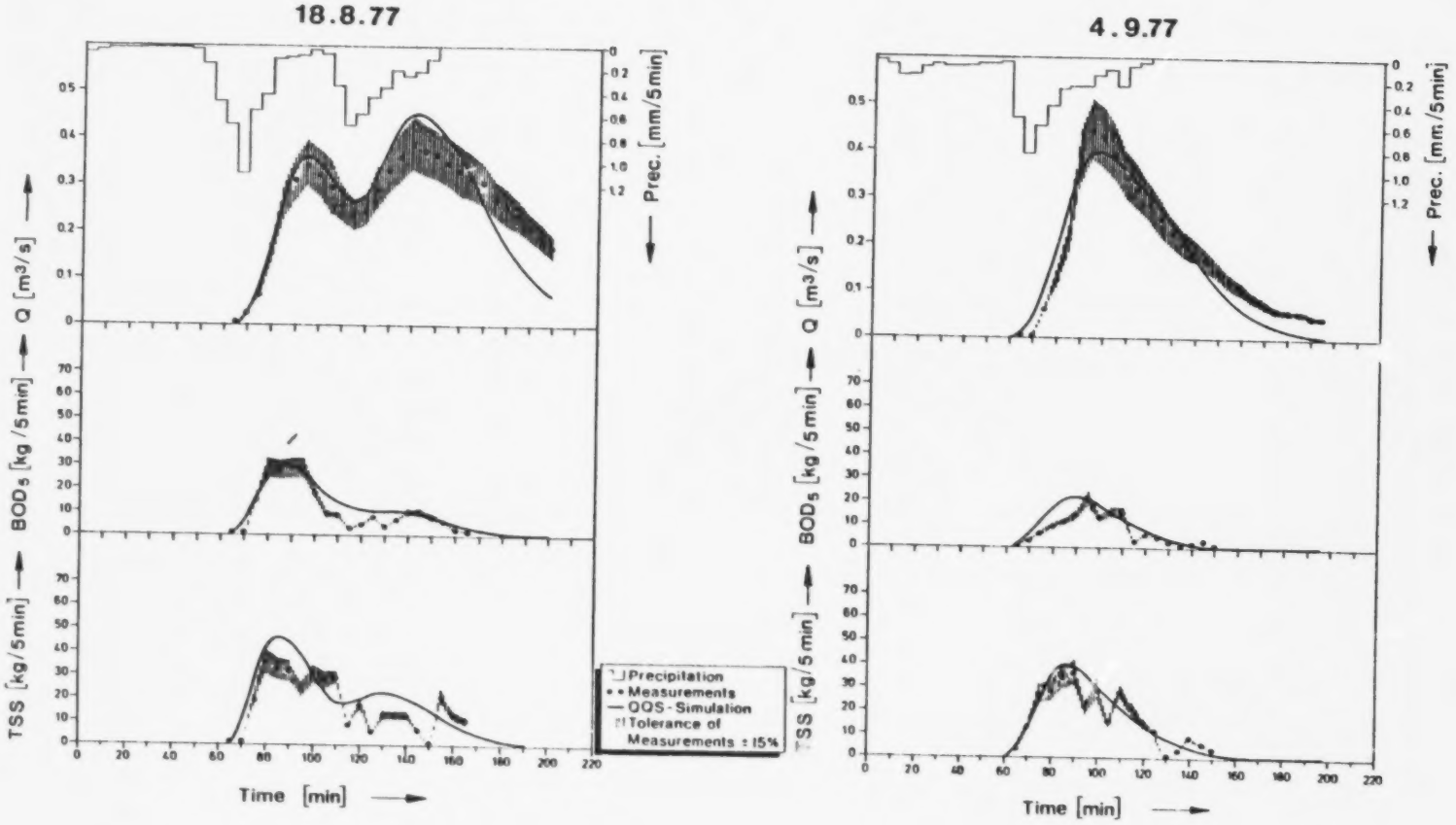

Figure 23. Comparisons with measurements; Ingolstaedter Strasse (96 ha), Munich, Germany; storm events of August 18 and September 4, 1977.

drawn at this manhole. The water depth recorder and an automatic sampler were located in a mobile shed stationed on top of the manhole. A calibrated measuring weir was installed on the rim to the pump well for flow evaluation. In Figure 24, flows are compared, for the storm events of September 5, 14 and 17, November 3 and December 2, 1976. In Figures 25, 26 and 27, comparisons are shown for flows, BOD_5, and total suspended solids for the storm events of September 15 and 28, 1976, and for June 29, July 13, August 9 and 18, and September 1 and 9, 1977.

For both the Ingolstaedter Strasse and Josef-Wirth-Weg metering stations, Manning dippers and Manning samplers were used. The equipment was adjusted so that sampling would start shortly after dry-weather flow runoff rates were exceeded. The samplers each had a capacity of 24 half-liter samples. The time interval at which the samples were drawn was set initially at 15 minutes but was later shortened to 7.5 minutes. This change was found necessary to record the first flush that occurred during the rising limb of the runoff hydrograph.

The metering stations were inspected daily when the recording charts for the dippers were exchanged and the equipment checked. From time to time, deposits that accumulated upstream of the metering weirs had to be removed. Samples taken were analyzed in the treatment plant laboratory for BOD_5, COD, and total suspended solids.

In the Pullach and Harlaching test catchments, mentioned earlier, precipitation was monitored within the catchment areas. Both the Ingolstaedter Strasse and Josef-Wirth-Weg test catchment are situated close to the meteorological station of Munich's Grosslappen treatment plant, and the rainfall recordings of this station were used for the runoff simulations for these two catchments.

Gothenburg Test Areas

The metering stations of the Bergsjoen and Torslanda test areas in Gothenburg, Sweden, were installed and operated by the Chalmers University of Gothenburg, Sweden.

The Bergsjoen test area has a size of 15 ha with an imperviousness of 40 percent. The catchment has an average slope and is drained by a separate storm sewer system. Land use is residential with high-rise apartment buildings. Details on the test catchment, the metering station and the data acquisition system have been reported (13). Measurements of flow, $KMnO_4$ demand, total suspended solids, lead, and phosphorus are compared with QQS simulations in Figure 28 through 32 for the storm events of May 8, June 27, July 10, 20 and 23, August 30, September 20, October 29 and November 11, 1973.

The Torslanda test catchment is a 105 ha residential area under development; it includes a school. The imperviousness at the time of monitoring was 16 percent. The area has an average slope. Details on the test catchment, the metering stations and the data acquisition system have been reported (17 and 18). Flow, COD, and total suspended solids measurements

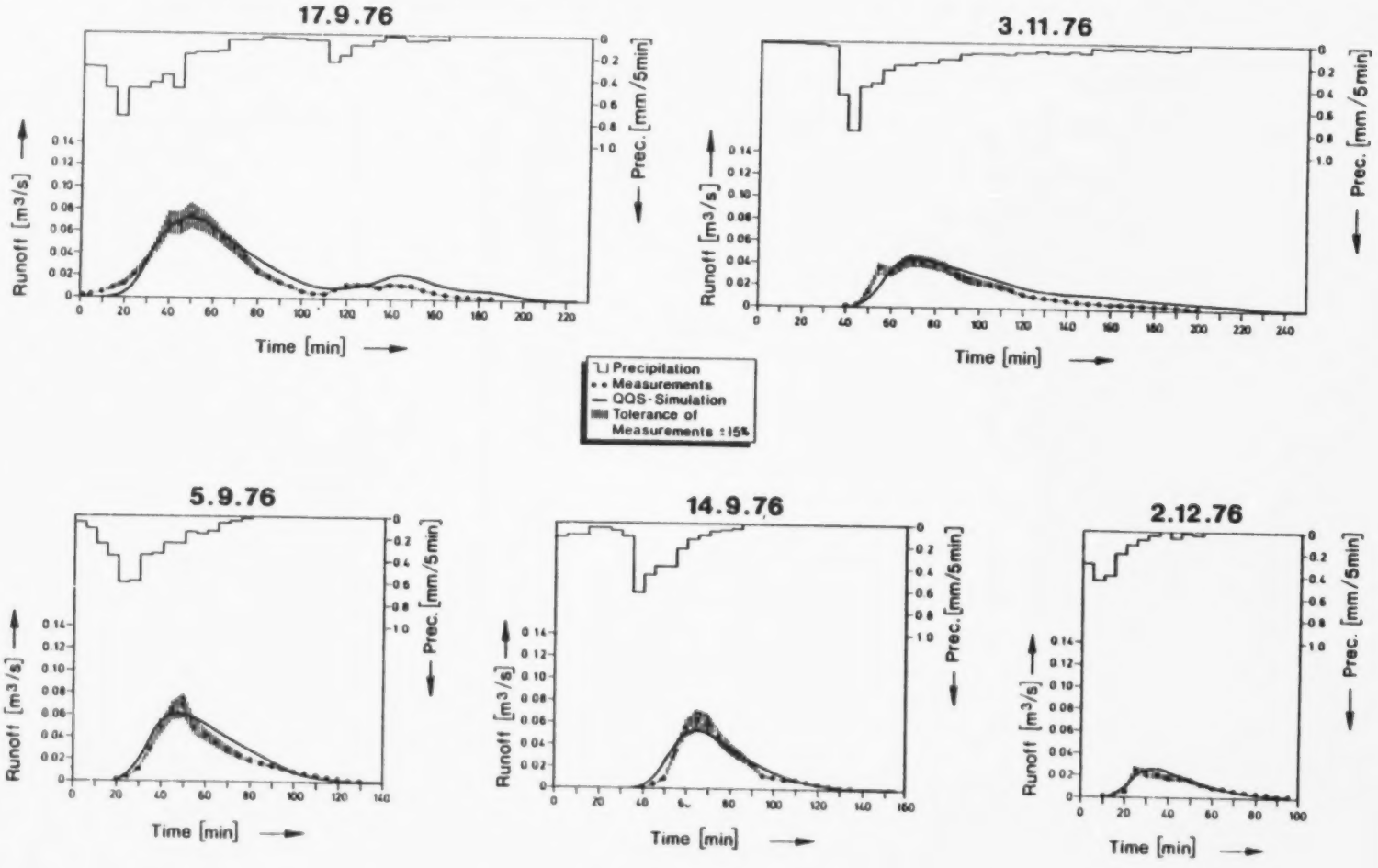

Figure 24. Comparisons with measurements; Josef-Wirth-Weg (34 ha), Munich, Germany; storm events of September 5, 14 and 17, November 3 and December 2, 1976.

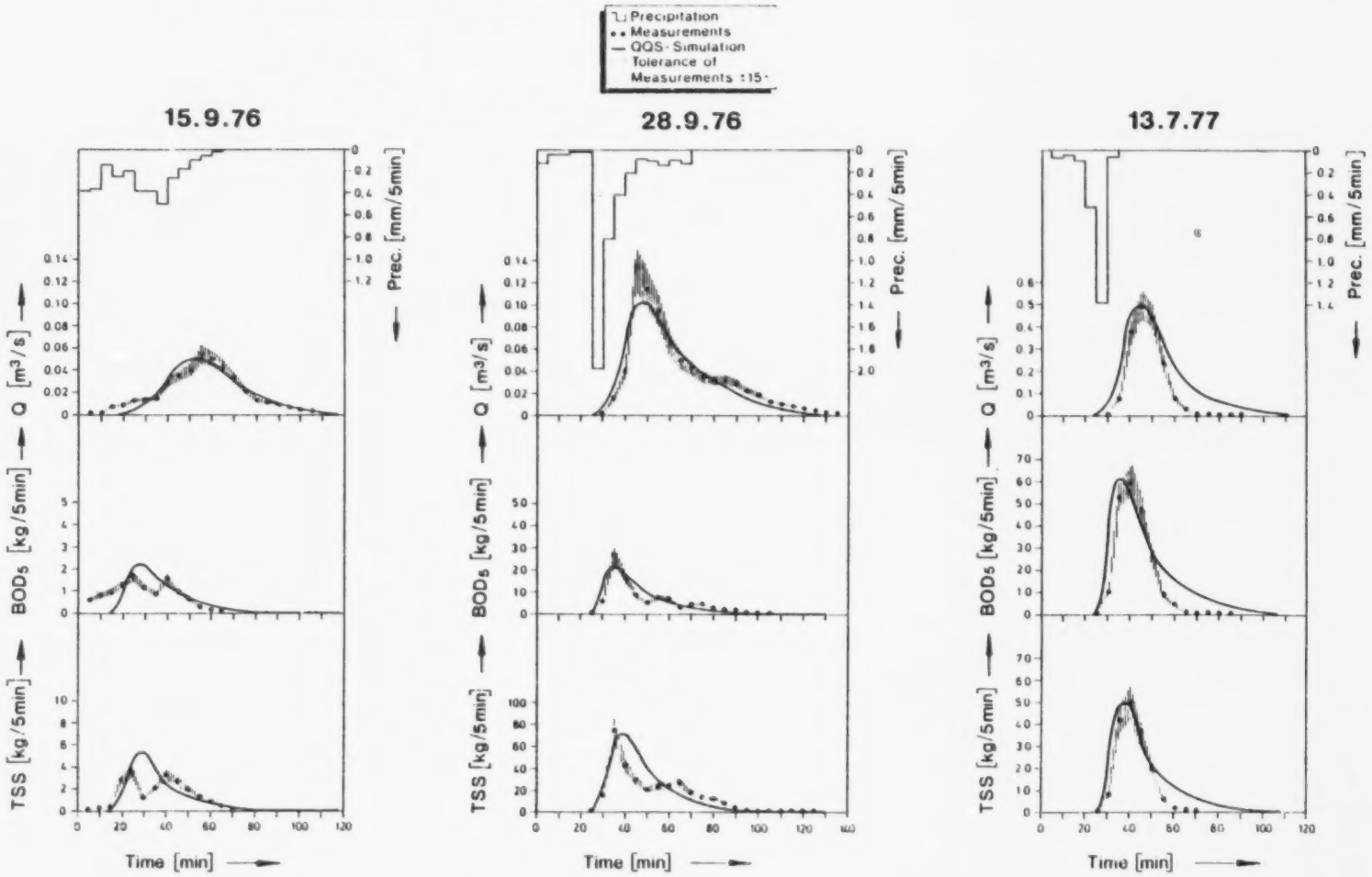

Figure 25. Comparisons with measurements; Josef-Wirth-Weg (34 ha), Munich, Germany; storm events of September 15 and 28, 1976 and July 13, 1977.

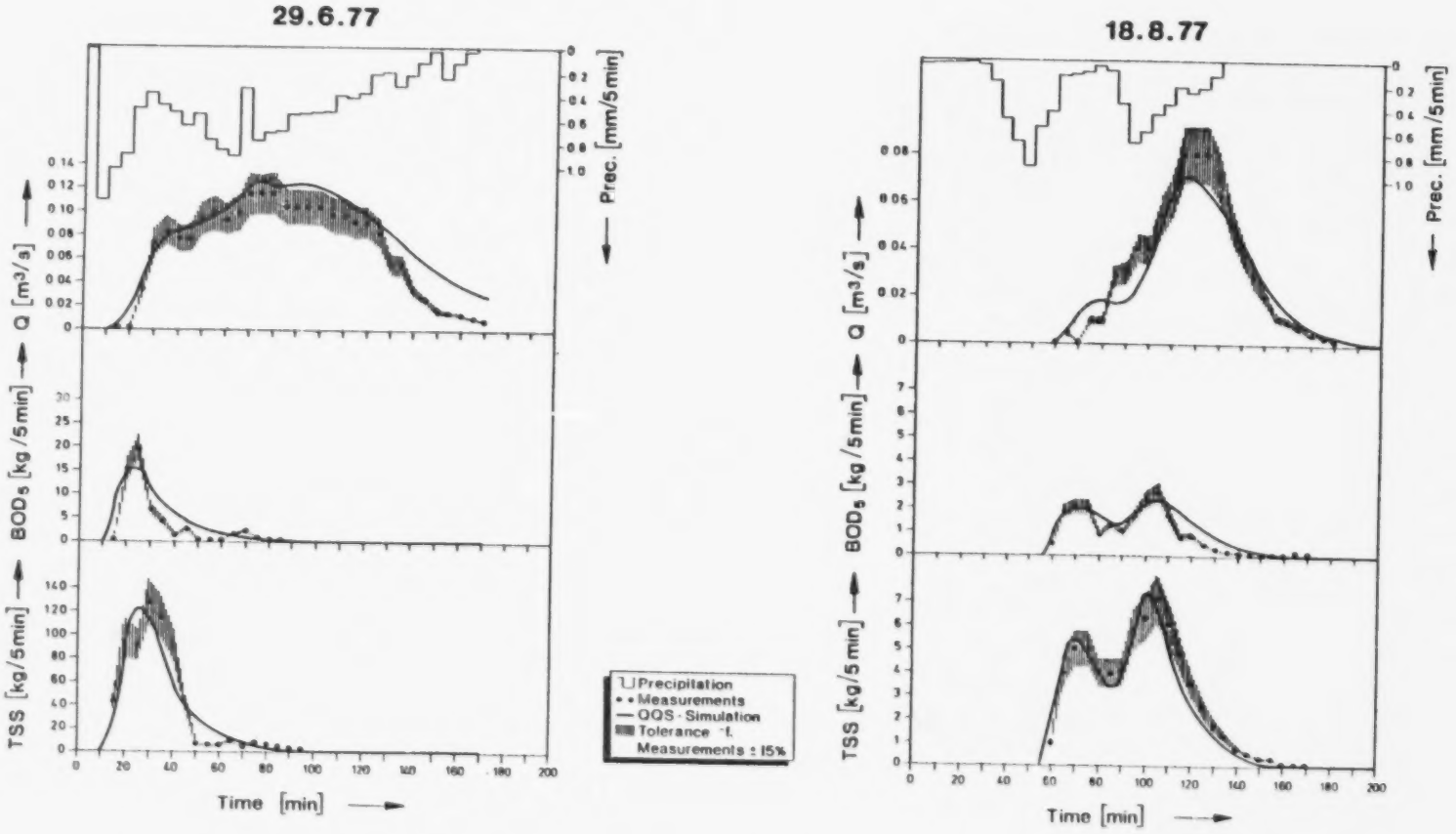

Figure 26. Comparisons with measurements; Josef-Wirth-Weg (34 ha), Munich, Germany; storm events of June 29 and August 18, 1977.

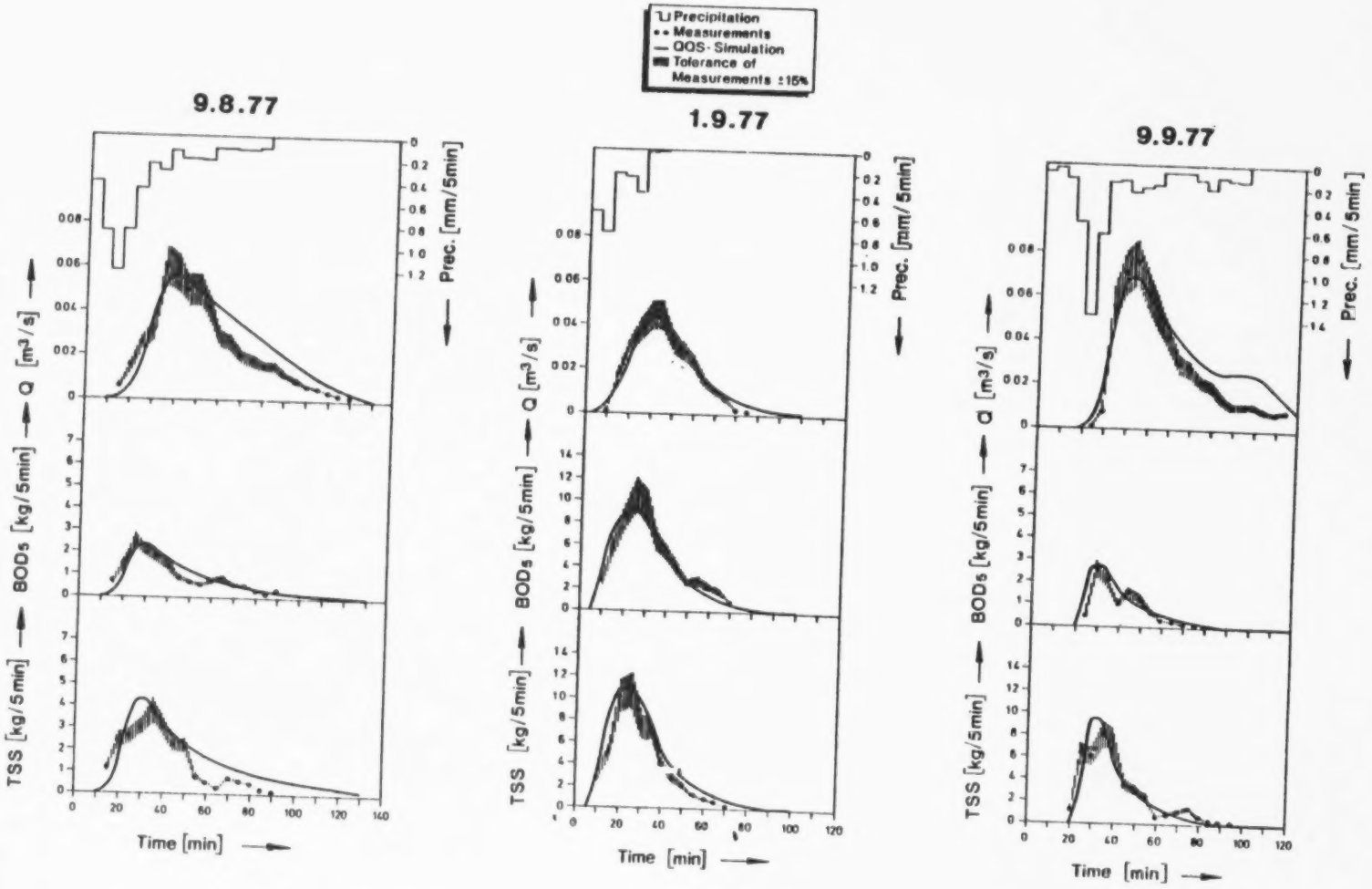

Figure 27. Comparisons with measurements; Josef-Wirth-Weg (34 ha), Munich, Germany; storm events of August 9 and September 1 and 9, 1977.

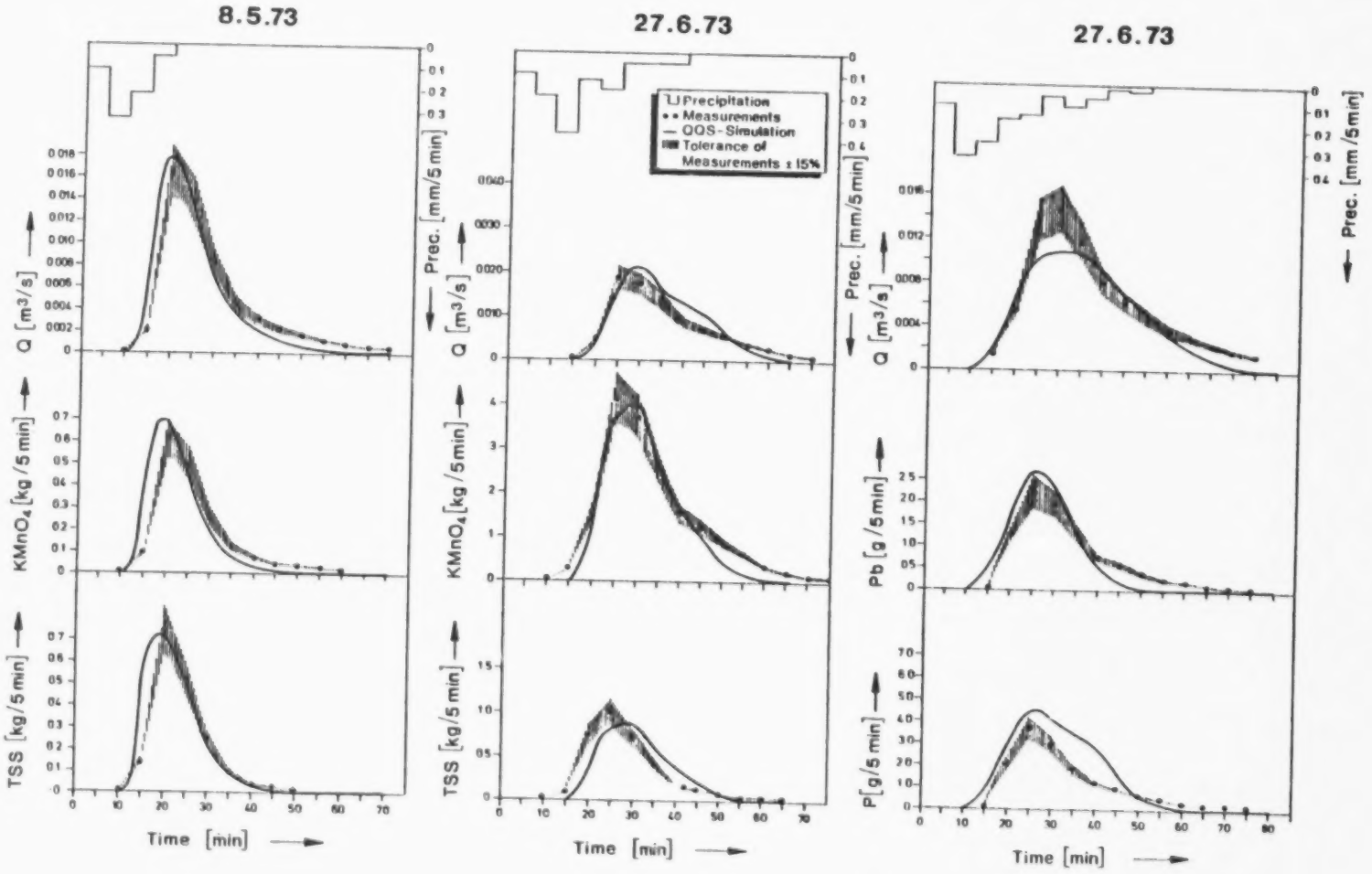

Figure 28. Comparisons with measurements; Bergsjoen (15 ha), Gothenburg, Sweden; storm events of May 8 and June 27, 1973.

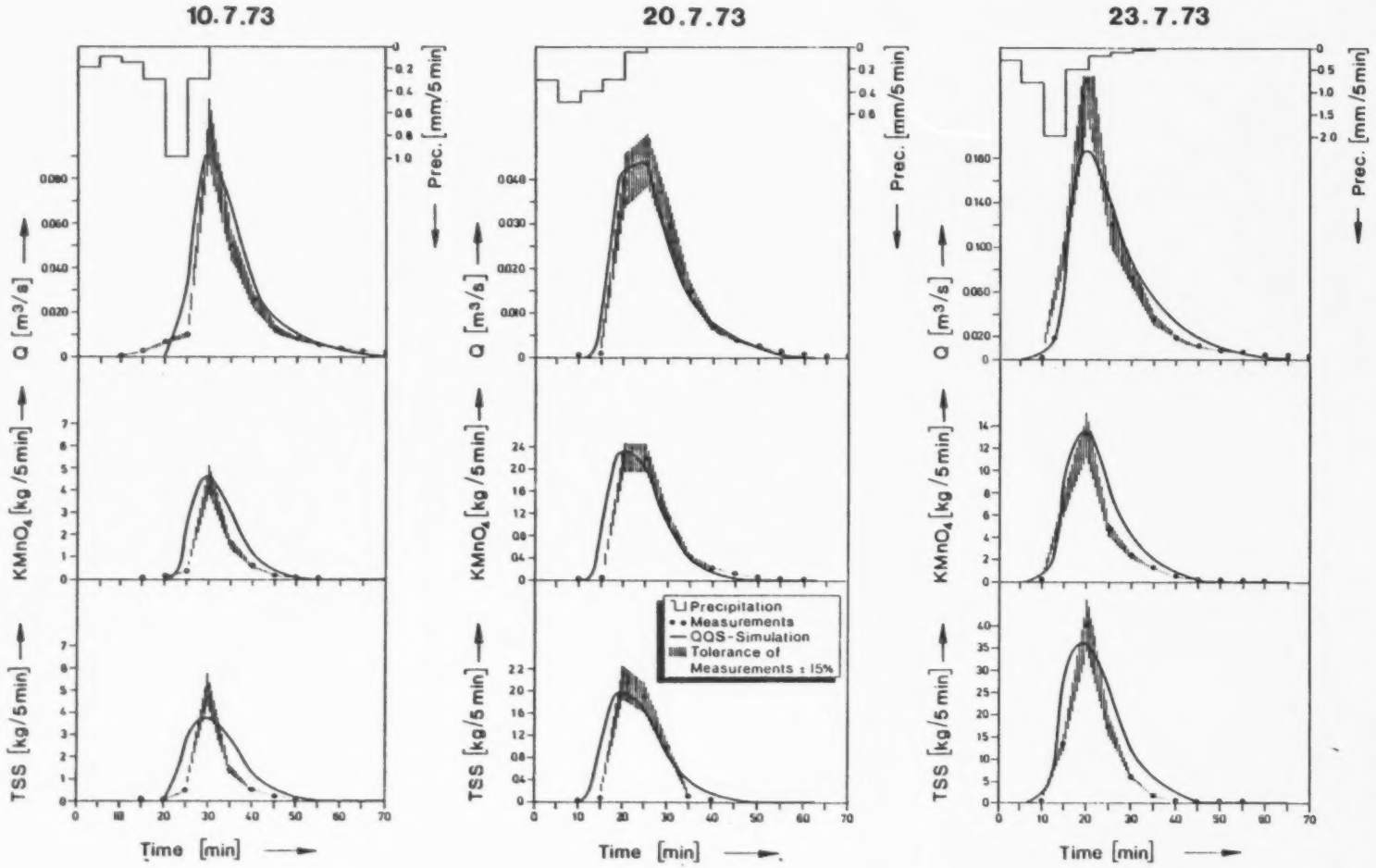

Figure 29. Comparisons with measurements; Bergsjoen (15 ha), Gothenburg, Sweden; storm events of July 10, 20 and 23, 1973.

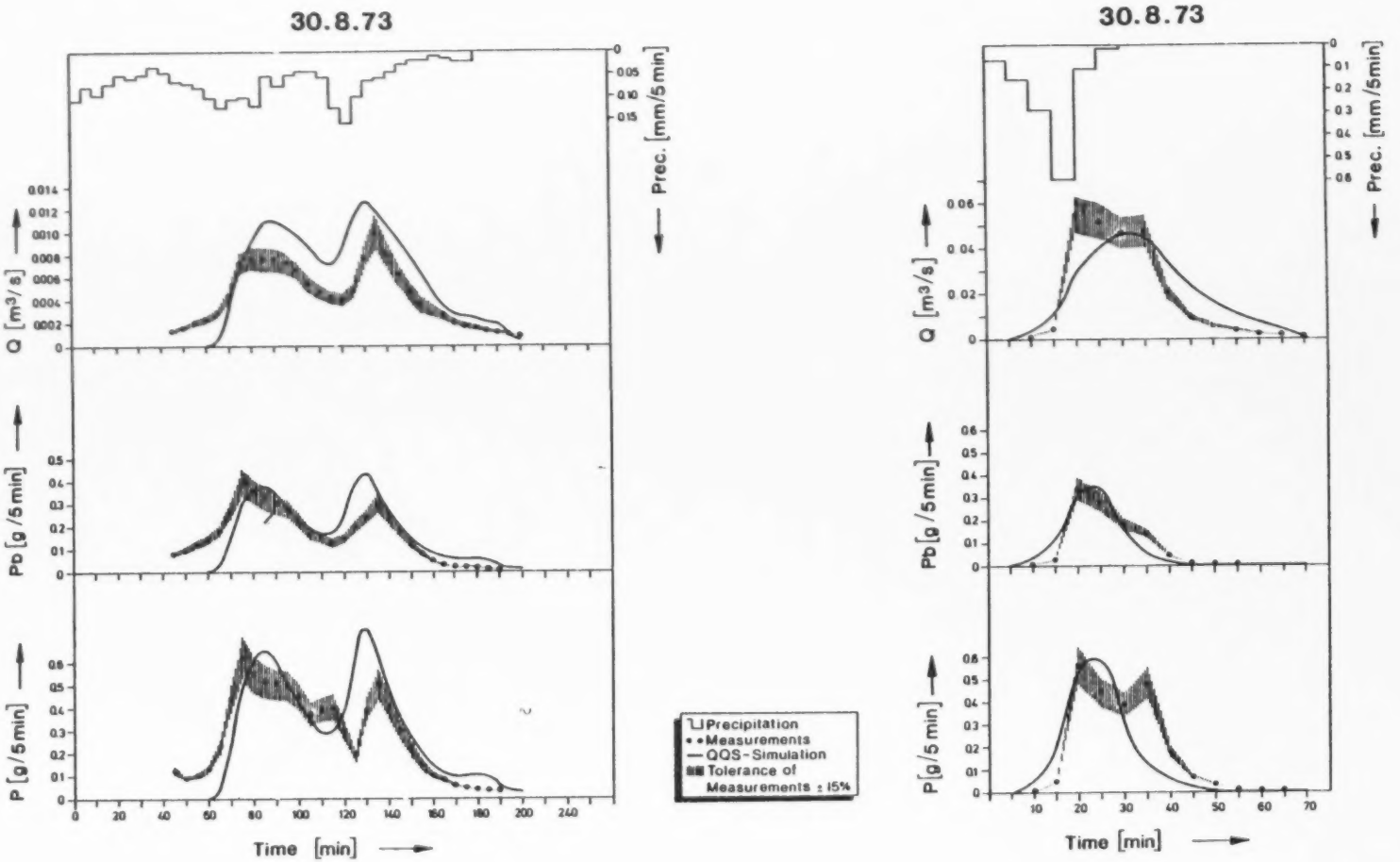

Figure 30. Comparisons with measurements; Bergsjoen (15 ha), Gothenburg, Sweden; storm events of August 30, 1973.

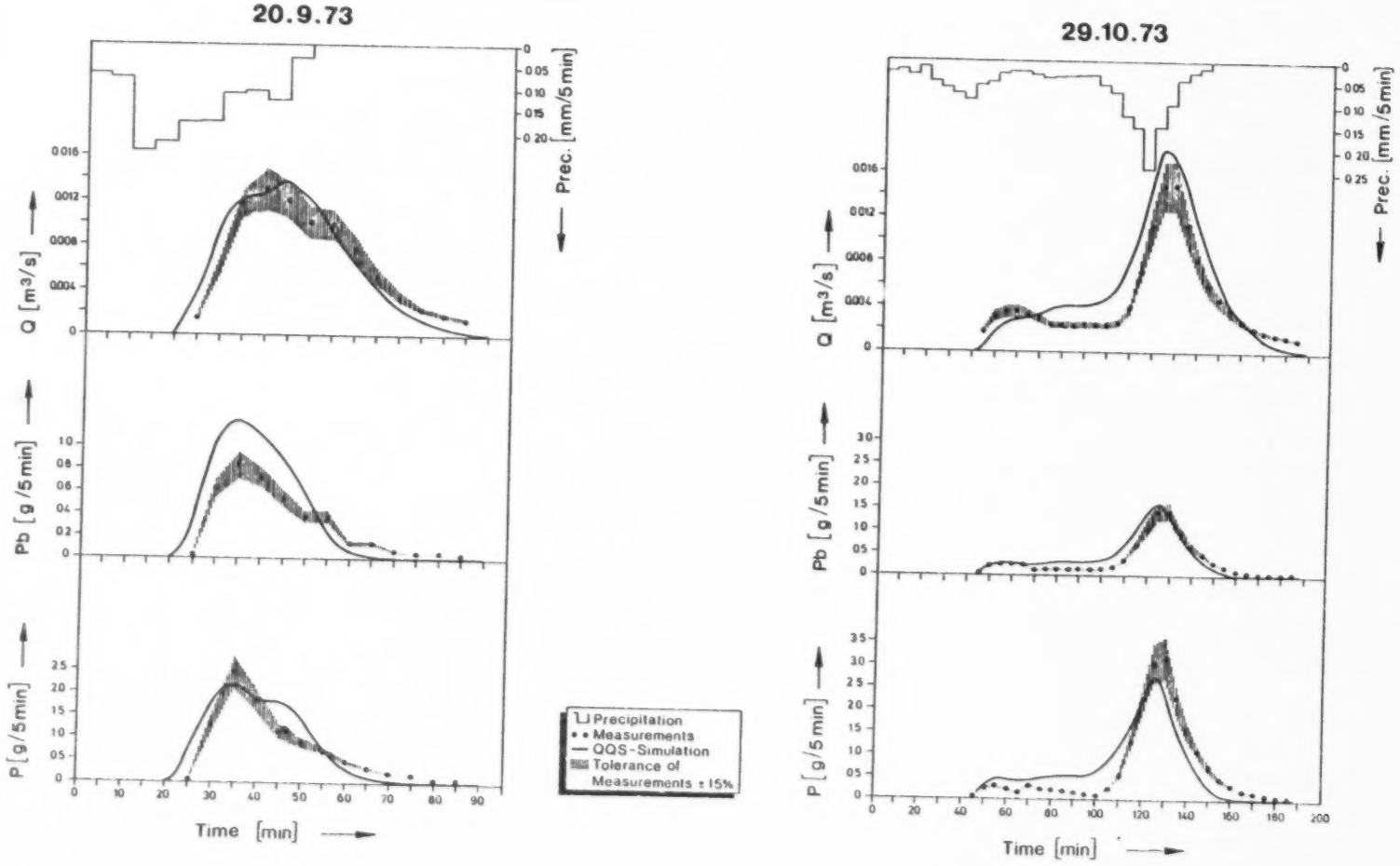

Figure 31. Comparisons with measurements; Bergsjoen (15 ha), Gothenburg, Sweden; storm events of September 20 and October 29, 1973.

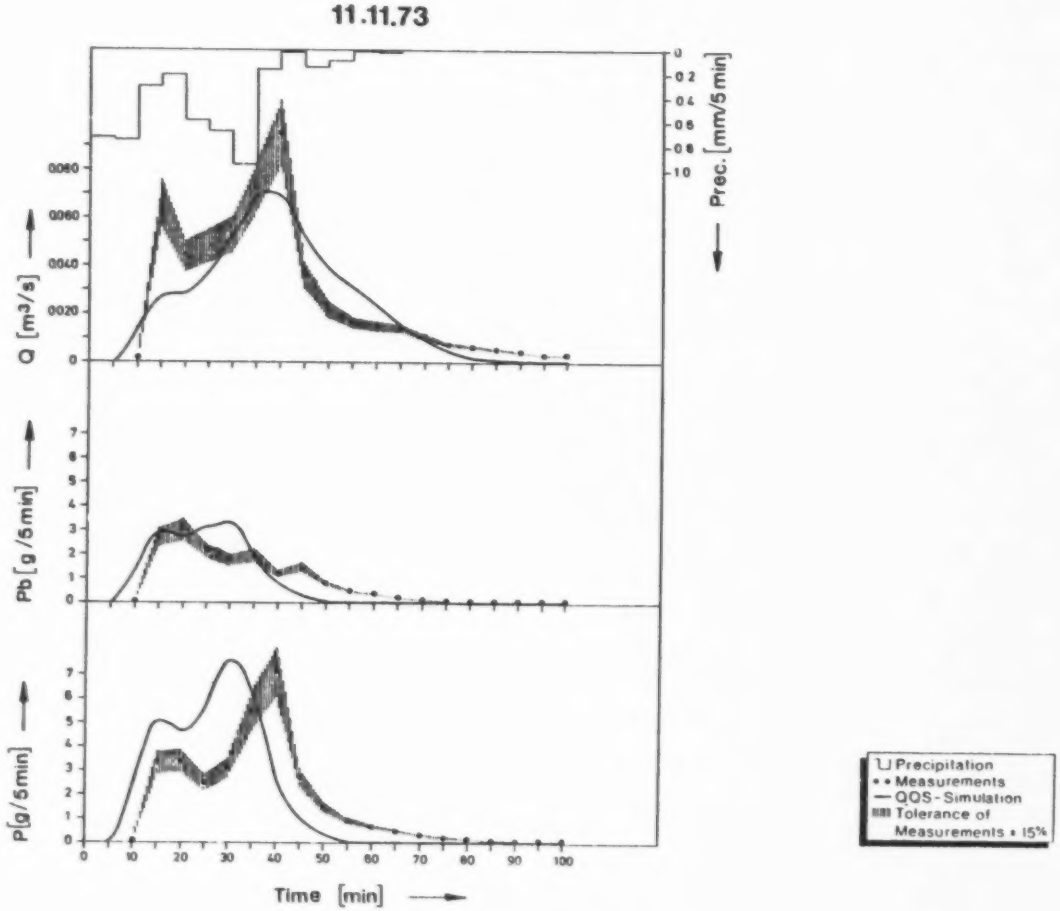

Figure 32. Comparisons with measurements; Bergsjoen (15 ha), Gothenburg, Sweden; storm event of November 11, 1973.

available for comparison with QQS simulations are shown in Figure 33 for the storm events of September 9, 12 and 27, and November 28, 1976.

Rochester Test Areas

Combined sewer overflow quantity and quality field data were compared with simulations for three test areas and two other sites in the network within a study by the Rochester, N.Y., Pure Water District.

Three of the test catchments are drained by combined sewers: Dewey Avenue (29 ha), Colvin Street (78 ha) and North Street (34 ha). Figure 34 shows comparisons of recorded and computed flows for the storm events of August 29 and 30, and September 11, 18 and 20, 1975, for all three catchments.

Site 8 in the Rochester, N.Y., sewer network comprises an area of approximately 390 ha with an imperviousness of 61 percent; it is drained by combined sewers and has mixed land uses. The slopes of the individual drainage areas vary from flat to average. In Figure 35, measurements of flow, BOD_5, total suspended solids, and fecal coliforms are compared with QQS simulation results for the storm events of May 31 and June 19, 1975.

Site 31 drains a combined sewer area of 878 ha with an imperviousness of 55 percent. The individual drainage areas represent mixed land uses and are of flat to average slope. The same parameters as for Site 8 are compared for Site 31 in Figure 36 for the storm events of June 5 and 19, 1975.

More details on the measurements and test areas may be found in the project report of the Rochester Pure Water District combined sewer overflow pollution abatement study (9).

Vancouver Test Areas

Vancouver, B.C., Canada, encounters mainly long-duration rainfalls but also short, high intensity storms. Therefore, data from both short storms and long rainfalls were used for catchment calibration of the QQS model in connection with an overflow abatement study of parts of the City of Vancouver.

The 74-ha area monitored at Alberta Street has an imperviousness of 42 percent and an average slope. The 27-ha area monitored at Mackenzie Street has an average slope and an imperviousness of 25 percent. Both areas are drained by combined sewers. For both sites, dippers and automatic samplers were installed in manholes. The samples drawn were analyzed for BOD_5, total suspended solids, and fecal coliforms. Runoff measurements of storm of up to 20 hours duration were compared with simulations from the QQS model.

The runoff behavior in the sewer network of the Vancouver study area is quite complex because of the interaction of several pump stations, control gates, syphons and overflows; therefore extensive calibrations of the QQS model throughout the study area were necessary.

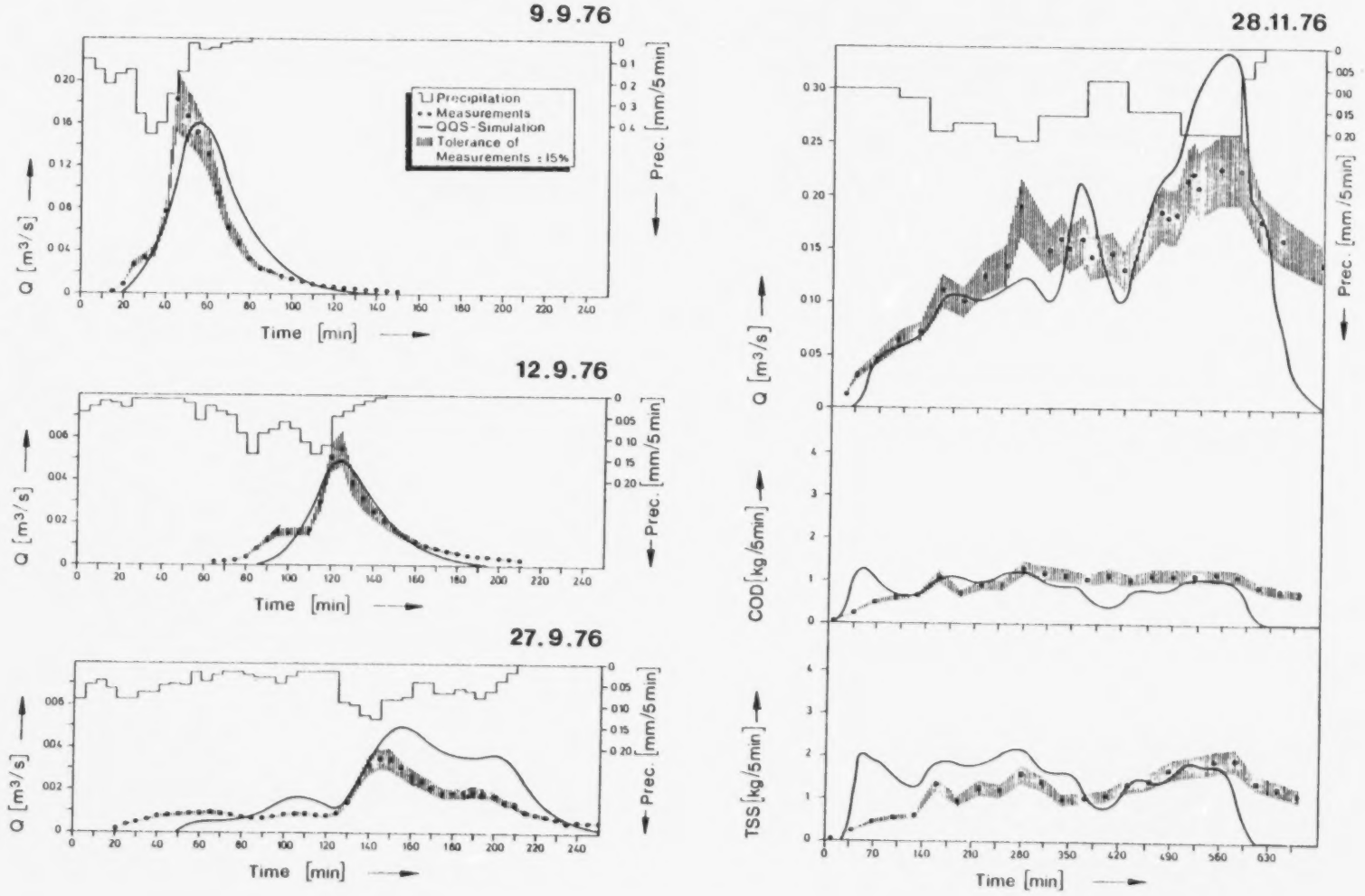

Figure 33. Comparisons with measurements; Torslanda (105 ha), Gothenburg, Sweden; storm events of September 9, 12 and 27 and November 28, 1976.

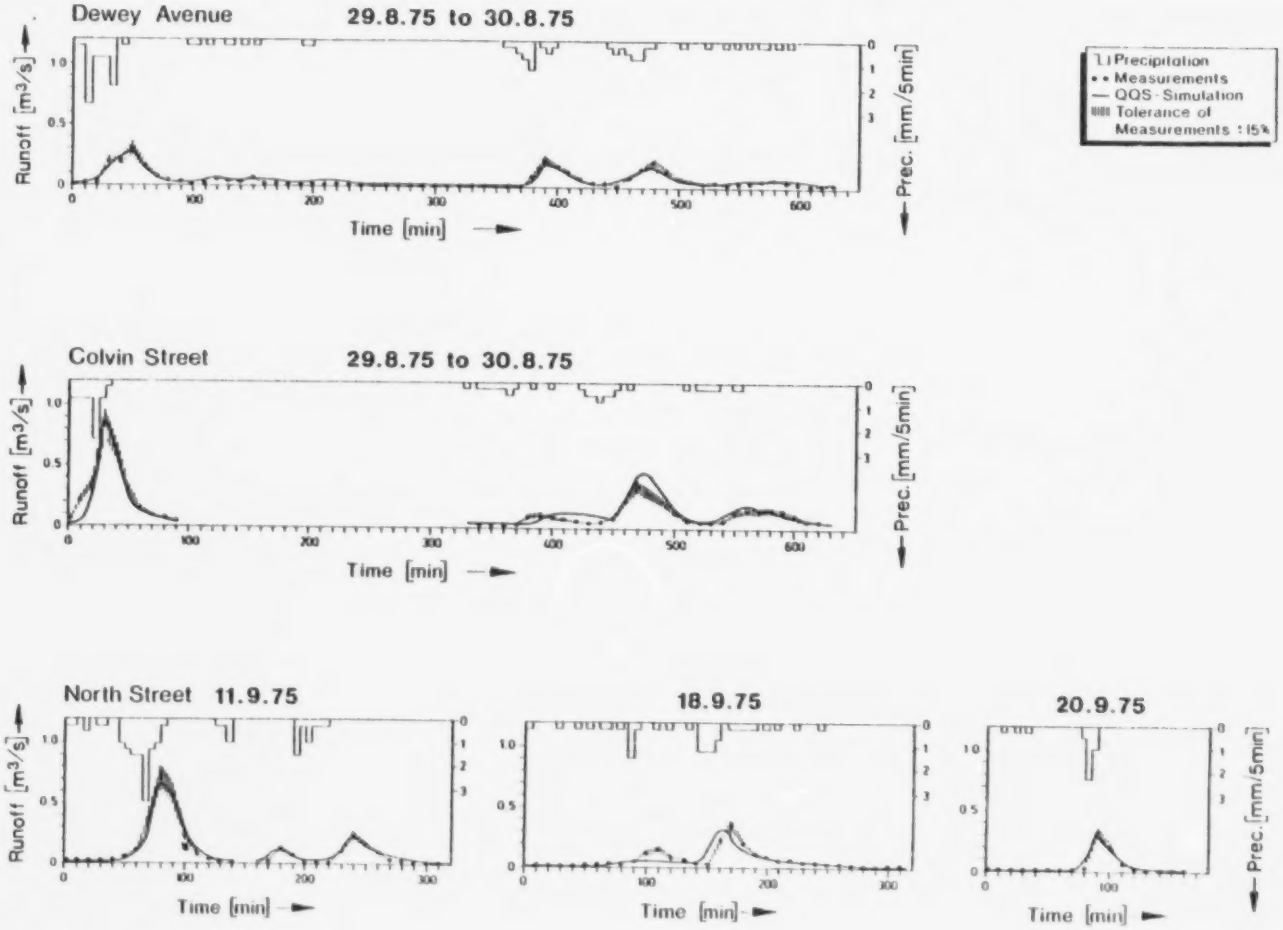

Figure 34. Comparisons with measurements; Dewey Avenue (29 ha), Colvin Street (78 ha), and North Street (34 ha), Rochester, N.Y., USA; storm events of August 29 and 30 and September 11, 18 and 20, 1975.

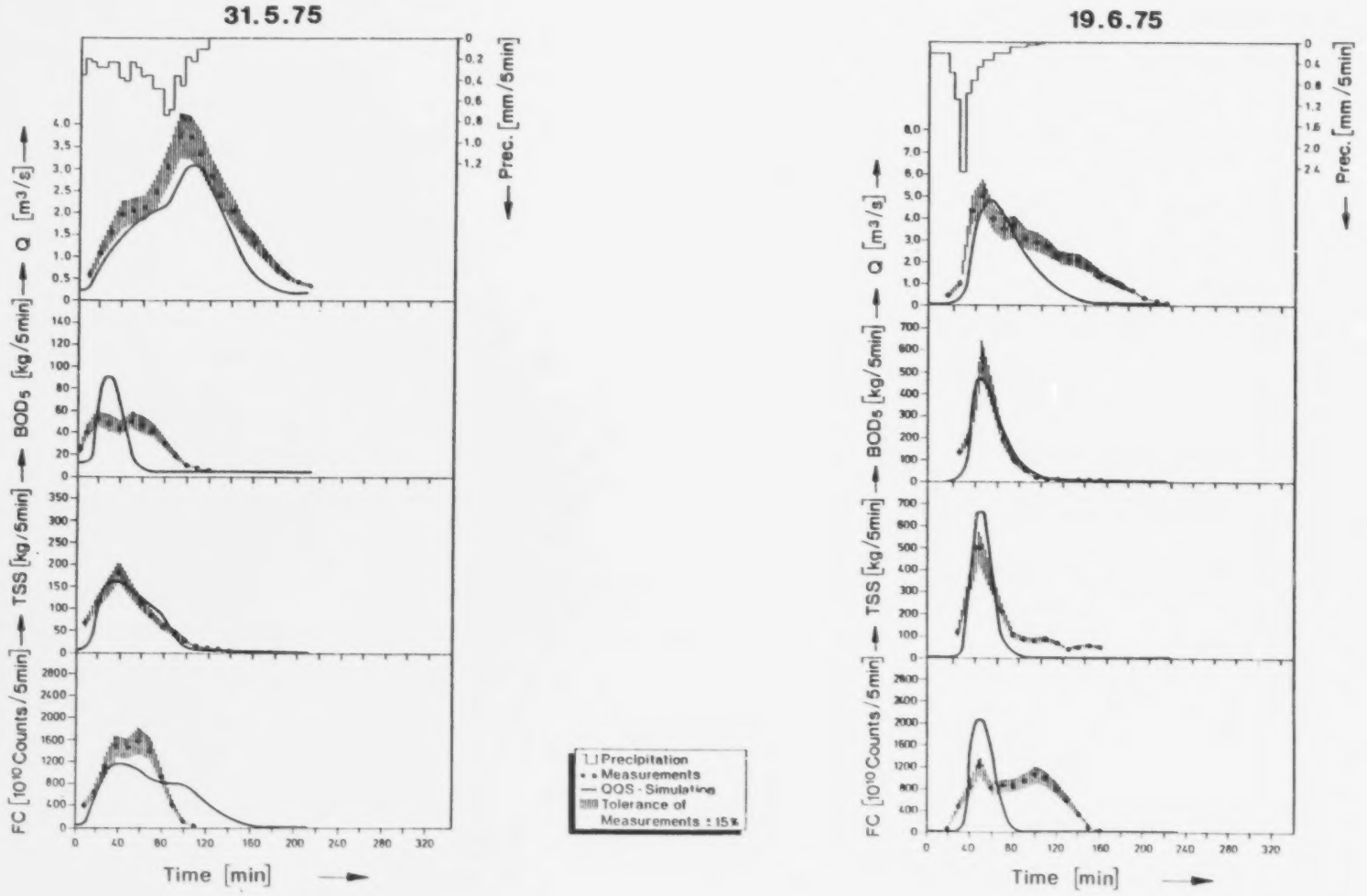

Figure 35. Comparisons with measurements; Site 8 (390 ha), Rochester, N.Y.; storm events of May 31 and June 19, 1975.

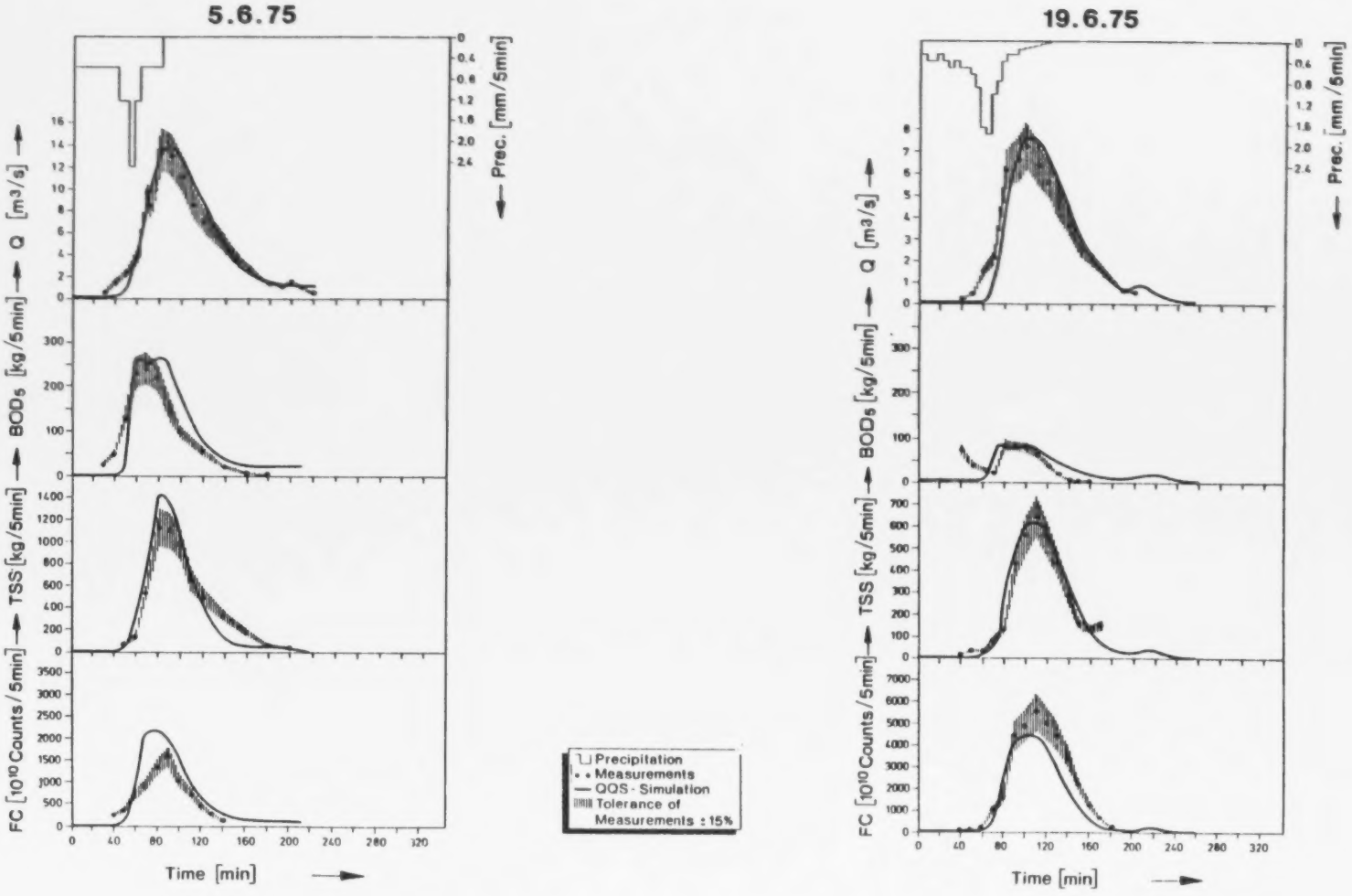

Figure 36. Comparisons with measurements; Site 31 (878 ha), Rochester N.Y.; storm events of June 5 and 19, 1975.

The calibration process involved comparisons of runoff quantity measurements at seven additional locations in the sewer network with QQS simulations. These locations comprise areas of up to 672 ha in size including drainage areas of different land uses and slopes that are mostly drained by combined sewers. Although eight storms were originally selected for use in the calibration runs, a number of four storms was tolerable for the final calibration of the overall system. Flow measurements were not synchroneously at all locations for all calibration storms.

Toronto Test Areas

In connection with a study involving the QQS model for the City of Toronto, Ontario, Canada, the measured runoff from two residential areas was compared with simulations. The one area is 49 ha in size and was measured at Jones Avenue; the second catchment comprises an area of 27 ha and was monitored at Castlewood Avenue. Both areas are of average slope and have an imperviousness of 50 percent. For calibration purposes four storm events have been used. At the time of this writing the pertinent study report containing more details was under preparation.

General Results

As a whole, it is concluded that the QQS methodology of lumped catchment simulation combined with detailed flow routing in the main and trunk sewers is able to reproduce field measurements closely for individual storms. It is then assumed that the model is sufficiently calibrated to be employed for continuous simulations for planning purposes. For any application, emphasis must be placed on the calibration and verification effort. This emphasis, of course, applies to all mathematical model applications.

COMPARISONS WITH A MORE DETAILED SIMULATION MODEL

Aside from the question of validating the QQS model with field measurements, it proved beneficial to compare QQS simulations with simulation results obtained with a more detailed simulation model. Such comparisons were made in connection with the Augsburg, Germany, overflow abatement study. Runoff quantities calculated by QQS, for a number of drainage areas of different land uses and other characteristics and for different locations in the main sewer system, were compared with corresponding simulation results previously obtained by detailed simulations with the HVM model. (The HVM-program package comprises approximately 10,000 Fortran statements and incorporates mainly a surface runoff and a sewer network flow simulation model. The surface runoff part transforms the time-dependent rainfall into time-dependent surface runoff solving the continuity and energy equations. These equations are also used for sewer network flow simulation of all sewer segments including all laterals. Due to the detail employed this method allows for single event simulation only.) Figure 37 contains comparisons for two drainage areas, one commercial and the other industrial. For nine different combined sewer overflow structures, the inflow and outflow hydrographs obtained by QQS simulations were compared with corresponding results from the more detailed HVM model in order to prove that the QQS model yields suffi-

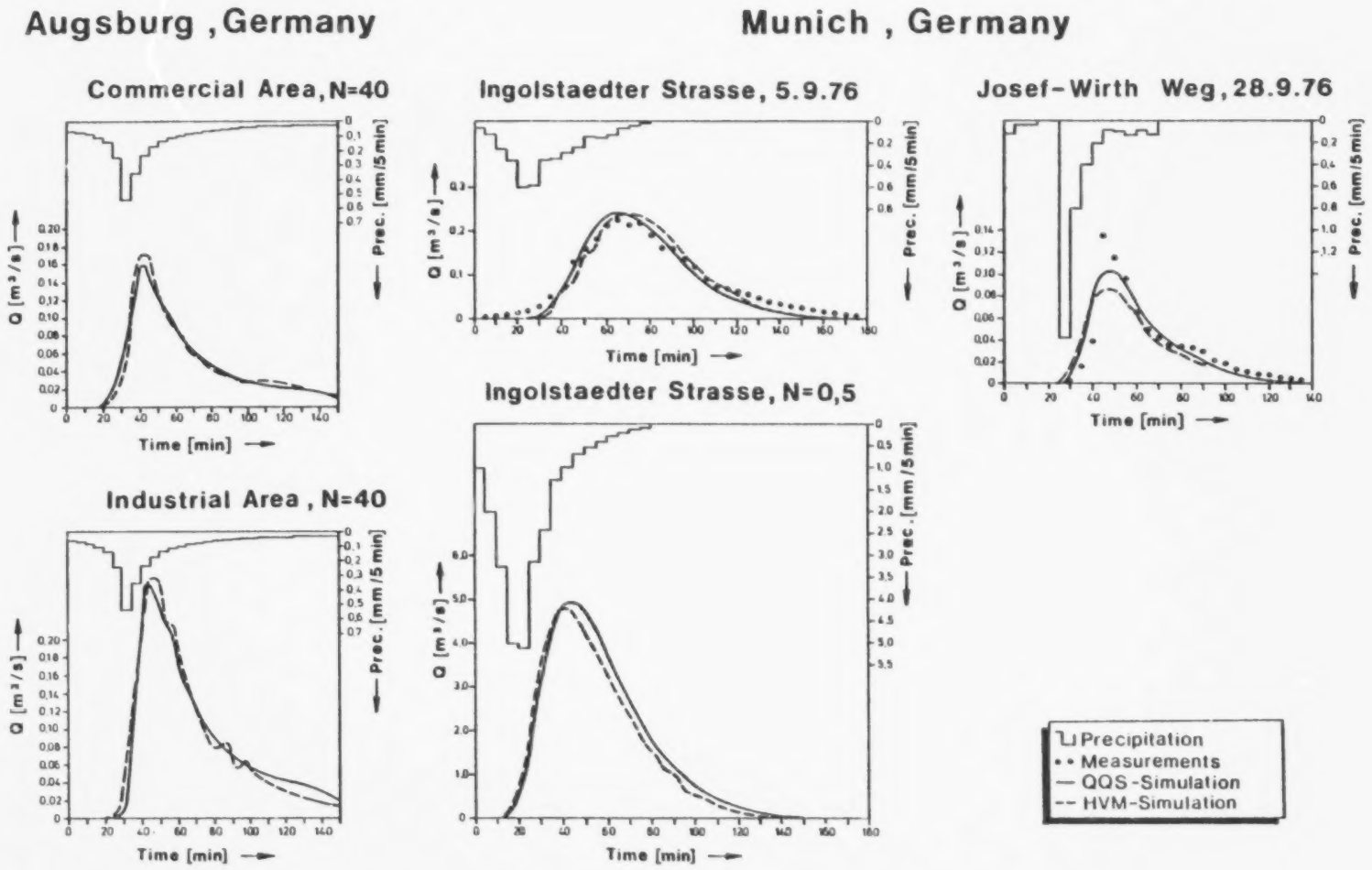

Figure 37. Comparisons of QQS catchment runoff simulations with pertinent HVM simulations.

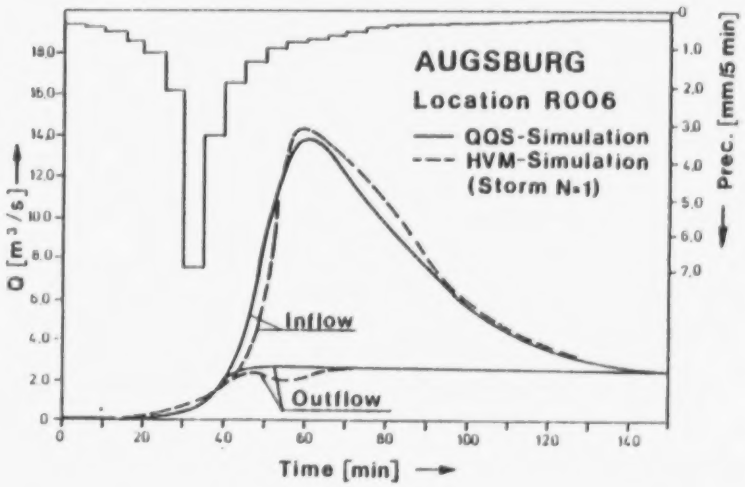

Figure 38. Comparison of QQS overflow simulations with HVM simulations for a once per year recurrence synthetic storm.

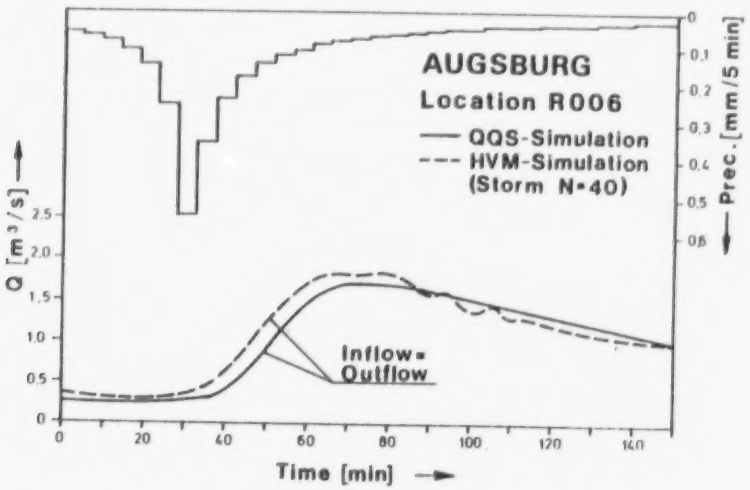

Figure 39. Comparison of QQS overflow simulations with HVM simulations for a 40 times per year recurrence synthetic storm.

ciently reliable results for planning of larger networks. Two examples of these comparisons are provided in Figures 38 and 39. These comparisons were made using storms with recurrences of approximately once per year (N = 1) and 40 times per year (N = 40).

For Munich, Germany, similar comparisons were made for different drainage areas and several locations in their main sewer system using synthetic design storms. One of the runoff comparisons for drainage areas (Ingolstaedter Strasse, N = 0.5) is shown on Figure 37. In addition, both QQS and HVM simulations have been compared with recorded rainfall-runoff events, such as in the examples given in Figure 37 for the Ingolstaedter Strasse (September 5, 1976) and Josef-Wirth-Weg (September 28, 1976) test areas.

The lumped and detailed simulations compare so well that, if there is sufficient trust in the detailed method, the unit hydrographs needed for the lumped method of the QQS drainage area runoff calculations may be derived using detailed simulation results such as from the HVM. The writer has employed this principle for deriving unit hydrographs, particularly for pervious areas.

Lastly, it should be noted that detailed simulation of all sewers in smaller drainage areas cannot be avoided if, for instance, final design of all sewers including lateral and collection sewers is the objective or if local flooding problems have to be studied.

SECTION 5

APPLICATIONS

AUGSBURG, GERMANY

The City of Augsburg, Germany, with a projected population of 470,000, is situated at the junction of the Lech and Wertach rivers. A master plan to span a planning period of 32 years was undertaken to determine the sequencing and timing of overflow abatement measures that should be taken to relieve the partially overloaded combined sewer network taking into consideration the future development of the city and its suburbs. At the same time, the heavy pollution of the Lech and Wertach rivers and of city creeks caused by combined sewer overflows had to be minimized and kept within set limits.

The master plan was developed on the basis of QQS and HVM calculations. Figure 40 shows the main and trunk sewer and receiving water systems, as defined for the QQS calculations. The study area consisted of 5,800 ha. First, QQS simulation results were utilized to estimate roughly the effect of different abatement alternatives. These measures were finalized using detailed HVM calculations. The final overflow abatement concept was investigated in terms of its impact on receiving water quality using QQS simulations. For expected conditions in the year 2010, continuous simulations were made using four years out of the last 15 years of rainfall records. Continuous simulation results were statistically analyzed for such variables as overflow duration, total, average and peak overflow volumes, BOD_5, and settleable solids.

The simulated overflows were then added to the corresponding background flows of the receiving water system, which includes the Lech and Wertach rivers and city creeks. Continuous simulation results of the runoff and pollution loads were statistically analyzed mainly for the increase of BOD_5 and settleable solids concentrations and their durations. This analysis was done for key points such as the junction of the Lech and Wertach rivers and downstream of the city area, where the greatest total impact of the city of Augsburg occurs on receiving waters.

The overall intent in developing the overflow abatement measures was to meet water quality classification "II" in the Lech river downstream from the city of Augsburg, which among other criteria allows for BOD_5 levels of 2 to 6 mg per l. No regulations, however, were available that defined the number and magnitude of violations acceptable per year. Rigid limits specified in the guidelines could not be met at all times, as is the case for any hydrological process. This uncertainty in criteria was overcome by analyzing the statistical results of the continuous QQS simulations in such a way that violations of the target classification "II" with its allowable BOD_5 level

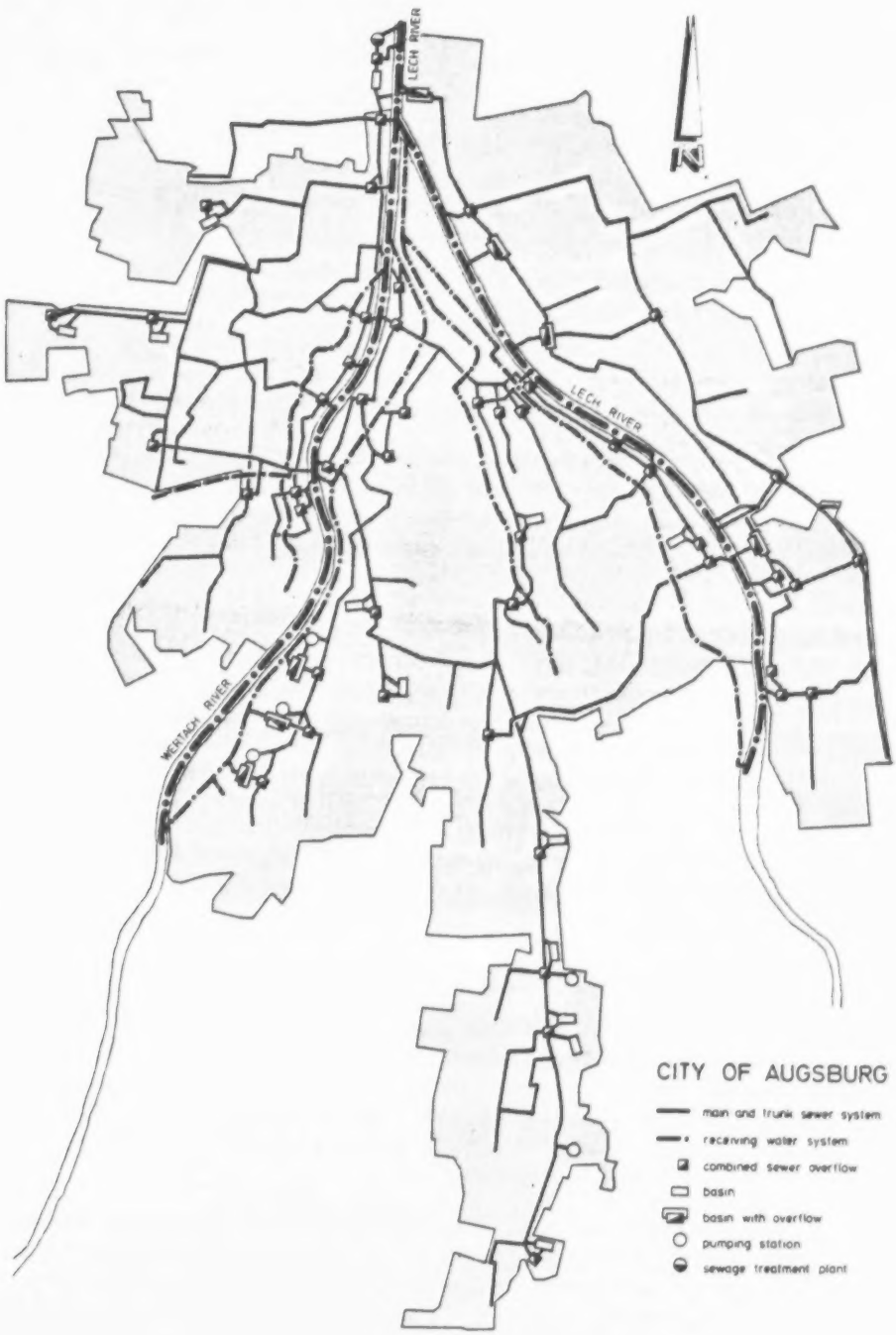

Figure 40. Main and trunk sewer and receiving water systems of Augsburg, Germany, as defined for QQS simulations.

of 6 mg per l could be interpreted in terms of average receiving water background BOD_5 levels. Figure 41 illustrates the total impact of the city's overflows on receiving waters, both including and excluding treatment plant bypasses and effluents. For example, one can read from the graphs in Figure 41 that for a background BOD_5 level of 2 mg per l, the target receiving water classification is contravened 14 times per year when treatment plant bypasses and effluents are taken into the consideration, but only approximately three times per year when treatment plant bypasses are excluded. The treatment level was fixed in this case.

Another guideline required that an average of 90 percent of the annual BOD_5 and settleable solids loads running off during storm events should be led to the treatment plant for processing. This provision was investigated using the average annual totals calculated by the continuous simulation.

The overflow abatement schemes suggested in this study called for mainly inline storage. Storage would be in detention channels and basins, which would be bypassed and emptied by pumping after major storm runoff occurrences, and utilized via branchings and cutoffs. This use of storage would guarantee a more equal usage of the overall storage volume of the sewer network. The study results also showed that additional increases in storage volumes within the sewer network would not yield further significant improvements in receiving water quality that would justify the additional costs.

MUNICH, GERMANY

The City of Munich, Germany, is drained mainly by a combined sewer system. Dry-weather flow and combined sewer runoff are mechanically and biologically treated at present in one treatment plant that discharges into a channelized branch of the Isar river which discharges into fish ponds.

The receiving water system of the combined sewer overflows is the Isar river with its connected creeks and channels. There are 33 overflow points that discharge into this receiving water system, some of which have overflows shortly after dry-weather flow is exceeded. Some of the overflow points are located at a part of the river that is dry or that carries only minor flows resulting from ground water infiltrations and lateral inflows for almost 300 days of the year.

The main purpose of the overflow abatement study for the City of Munich was to guarantee, in the receiving waters downstream from the urbanized area of Munich, the maintenance of water quality classification "II", mentioned above in connection with the City of Augsburg. To satisfy this standard, overflow abatement measures, that would reduce the frequency and duration of overflows, had to be developed.

The project was divided into four phases: data collection and preparation, assessment of existing conditions, development of overflow abatement measures, and presentation of evidence that the suggested measures would satisfy the water quality standards. The pollutant parameters investigated

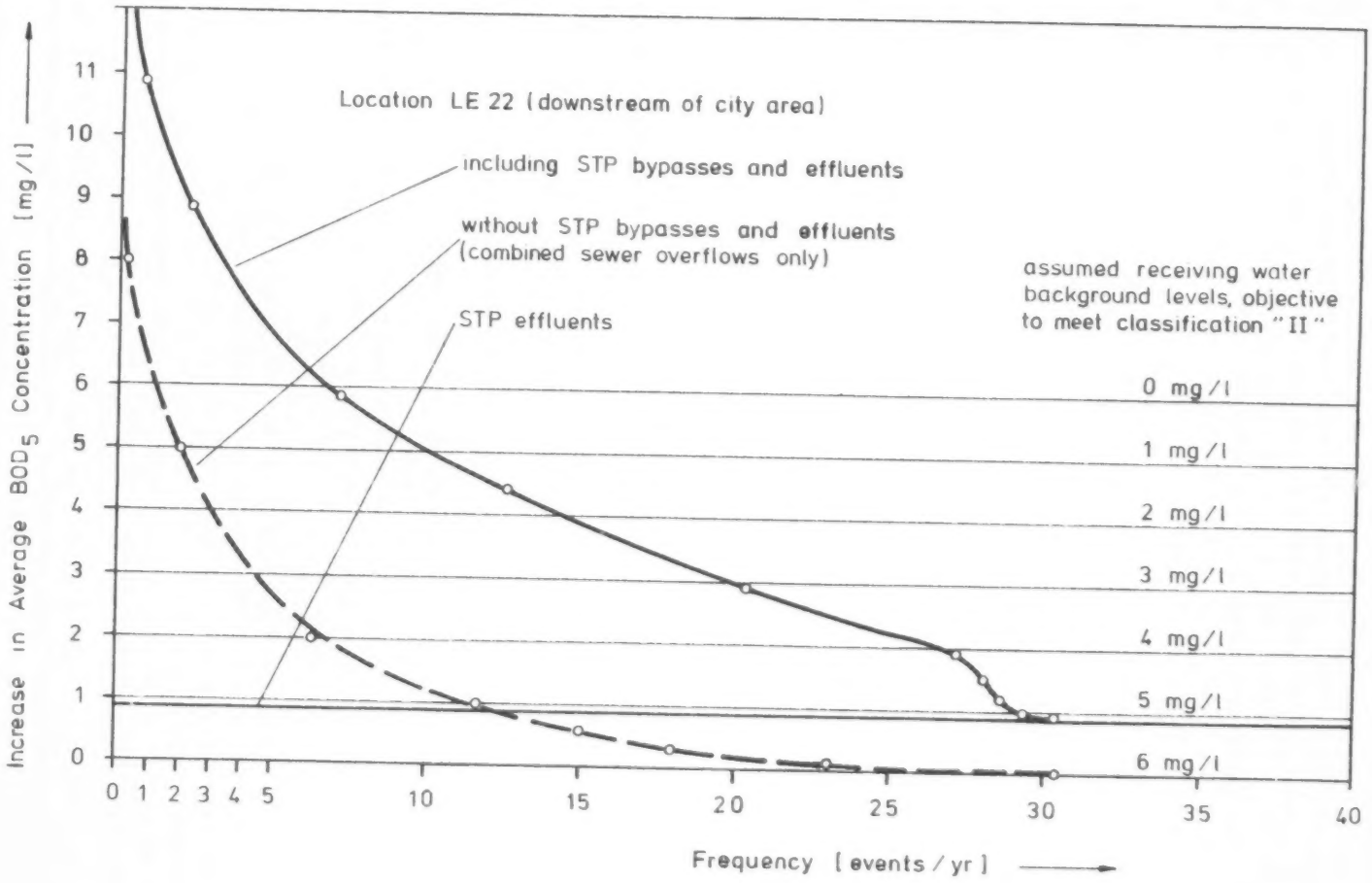
Location LE 22 (downstream of city area)
including STP bypasses and effluents
without STP bypasses and effluents
(combined sewer overflows only)
STP effluents
assumed receiving water
background levels, objective
to meet classification "II"
0 mg/l
1 mg/l
2 mg/l
3 mg/l
4 mg/l
5 mg/l
6 mg/l
Increase in Average BOD5 Concentration [mg/l]
Frequency [events/yr]
0 1 2 3 4 5 10 15 20 25 30 35 40
0 1 2 3 4 5 6 7 8 9 10 11

Figure 41. Total impact of BOD_5 on the Lech River, Augsburg, Germany, as predicated by QQS simulations.

were BOD_5 and total suspended solids. The study area for existing conditions has a size of approximately 13,600 ha and 1.56 million inhabitants are connected to the present sewer network. Simulation for future conditions were based on an area of 20,800 ha and 3.17 million inhabitants. This increase is due to additional future connections of suburban areas to the Munich sewer system. This future system also includes a second treatment plant the location of which already was predetermined. The trunk sewer and receiving water system used for the QQS simulations is shown in Figure 42. The computer program had to be adjusted to accommodate for the study area size. The QQS model was calibrated on a variety of flow and pollution measurements from four test catchments and the treatment plant intake.

For simulation purposes, the rainfall record of three meteorological stations located within the study area were used. Thus, the temporal and spatial variations of rainfalls were considered to some extent. Continuous simulations with the QQS program have been performed on the basis of four representative years selected from the continuous records of 20 years from each station.

From continuous simulation results of existing conditions the present impact of combined sewer overflows on the receiving waters was defined. Investigating the calculated differences in the individual overflow frequencies and loadings, overflow abatement alternatives were developed, such as adjustment of overflow weir heights, cutoffs, additional inline and offline storage. The abatement scheme selected is a combination of above measures and includes an additional offline storage volume on the order of 250,000 m^3 and an extra inline storage of approximately 300,000 m^3. For this scheme the required criteria could be met.

Especially during the phase of development of overflow abatement measures QQS simulations were found to quickly indicate the effectiveness of individual measures with respect to receiving water loadings. The detailed layout of the abatement scheme selected was finalized using the hydraulic simulation package HVM.

ROCHESTER, N.Y.

The combined sewer system of the City of Rochester, N.Y., with a population of 320,000 and an area of 5,300 ha, discharges pollutants into the Genesee River. This pollution load causes a significant depression in dissolved oxygen levels and increases fecal coliform indicator organisms. Within the Rochester Pure Water District, combined sewer overflow pollution abatement program, application of mathematical models has helped in the assessment of present conditions and in the definition of an abatement scheme which would comply with New York State Department of Environmental Conservation stream classification "B", which is aimed at the best usage for the resource, contact recreational use, and all other uses, except as a source of potable water.

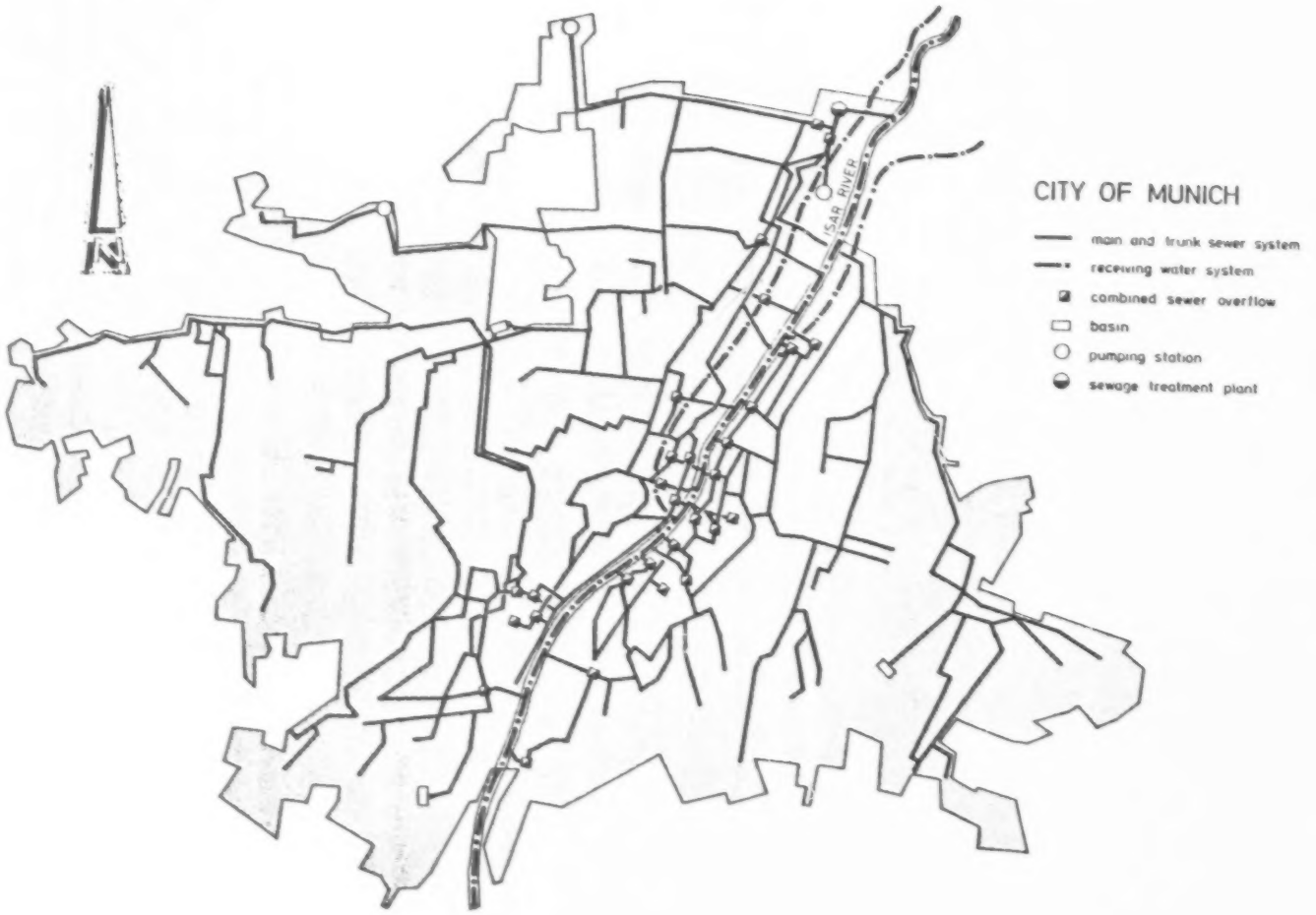

Figure 42. Main and trunk sewer and receiving water system of Munich, Germany, as prepared for QQS simulations.

The computer program was adjusted to accommodate for the size of the study area and was calibrated using local measurements. Continuous simulations of the runoff and overflow behavior of the main sewer network of the City of Rochester (Figure 43) were made for 8 years selected from a rainfall record spanning 15 years. The overflow events simulated with the QQS model were combined with recorded river flows and an average annual number of contraventions of the classification "B" was derived for each added storage and treatment combination investigated.

The model output was also used to determine the total BOD_5 loads presently overflowing into the Genesee River on an average annual basis, and the reductions of annual BOD_5 loads to be expected from storage facilities of various sizes. Total suspended solids and fecal coliforms were also investigated.

A cost-effective system with a storage volume on the order of 300,000 m^3 was found to comply with the stream standards. The results of this study have been presented previously (5 and 16) and are contained in a study report (9).

VANCOUVER, B.C., CANADA

The main objective of a study using QQS for an area of the City of Vancouver, B.C., Canada, facing the shores of English Bay and False Creek, was recreational use with full body contact while keeping bathing beaches open for a maximum number of days in the season. There are two criteria which had to be met. One, the Rawn Report, published in 1953, provides criteria for design based on overflow events and is basically addressed to the maintenance of the recreational waters in English Bay. It is advisory only and is not legally binding. However, the Pollution Control Branch of the Government of British Columbia, established in 1967, enforce guidelines for combined sewer operation which apply to continuous, not seasonal discharges. To satisfy their requirements, data for the annual performance of the sewer improvements to be developed were required. In addition seasonal information to justify any of the recommendations to the City's administration were desired.

The study area has a size of approximately 3,000 ha and 110,000 inhabitants are connected to the storm and combined sewer system of the area under investigation. The network of the study area contains almost all features found in sewer systems, such as branches, outfalls, overflows, detention basins, pumping stations, time-dependent and water surface-dependent operational control gates and syphons. Figure 44 shows a schematic of the main sewer system of the study area. The complexity of the network, the substantial external loadings that enter the study area, and backwater effects from reaches downstream of the study area, called for some adjustments of the computer program and an extensive calibration effort for this QQS application. Observations were available at seven locations within the network and at two sewer system overflow points. Although eight storms were originally selected for use in the calibration runs, a number of four storms was tolerable for the final verification of the overall system. Hereby flow

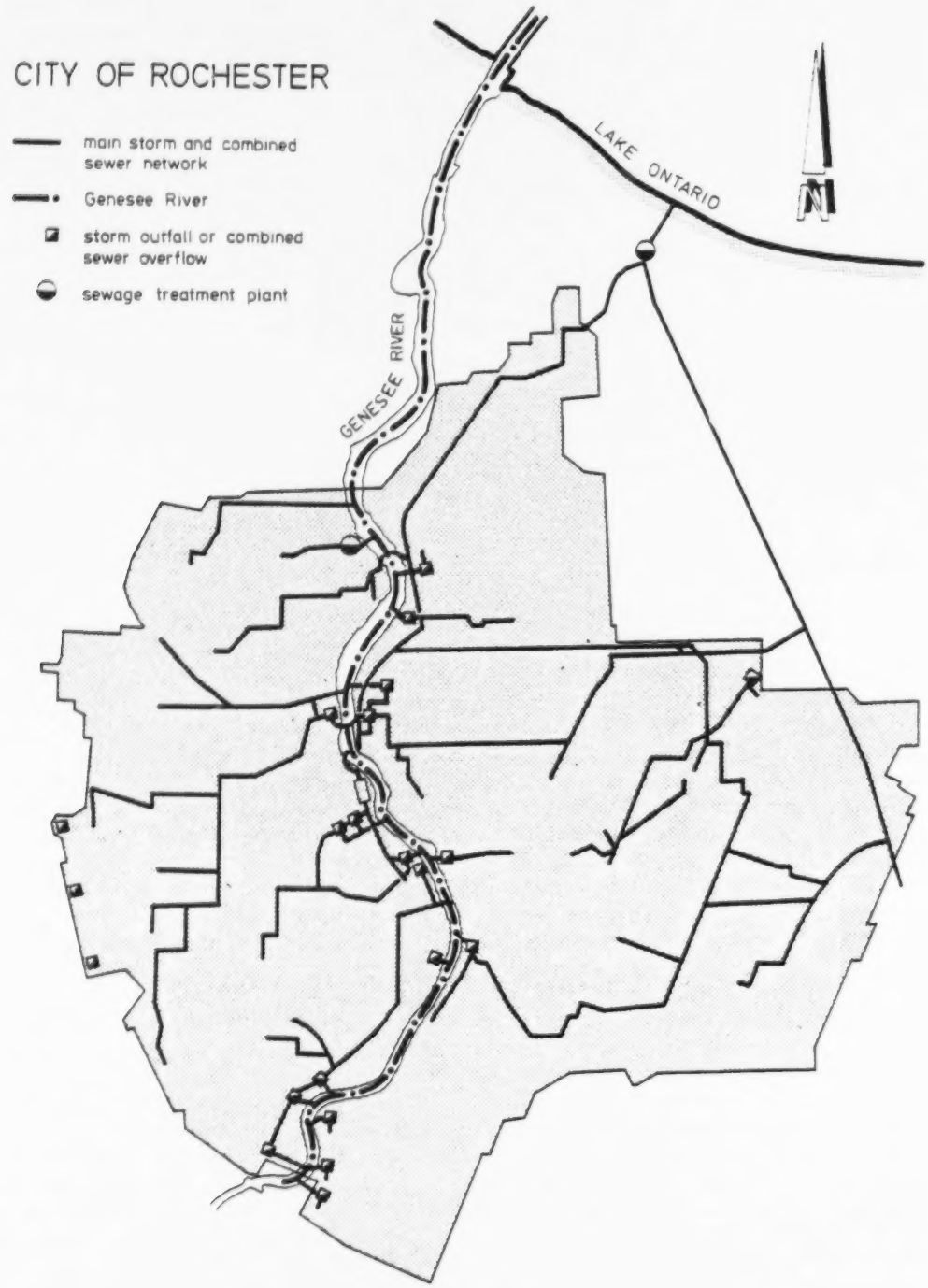

Figure 43. Schematic of the main and trunk sewer system of Rochester, N.Y.

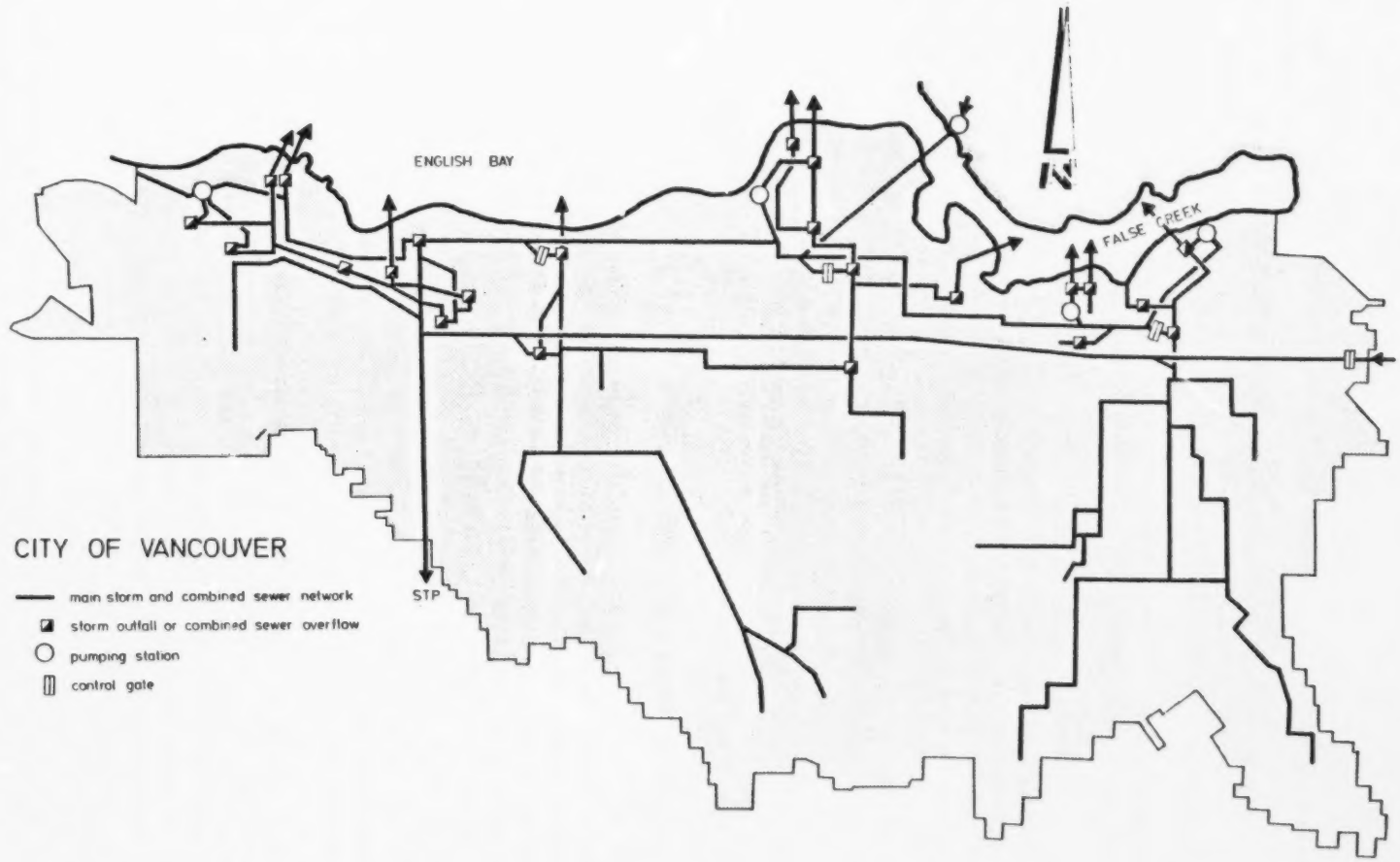

Figure 44. Schematic of the main and trunk sewer system of Vancouver, B.C., Canada.

measurements were not simultaneously available at all locations for all calibration storms.

After the successful calibration the impact of the existing system on the receiving waters was assessed. This assessment was derived from continuous rainfall-runoff simulations with the QQS program of five summer periods (May to September) and of three winter periods (October to April). The periods were selected from 18 years of rainfall records. The parameters BOD_5, total suspended solids, and fecal coliforms were investigated.

On the basis of this problem identification a number of possible alternative measures to abate the combined sewer overflow problem was investigated. These measures included upgrading of the inflow to the treatment plant, changes in gate settings, additional storages and flow diversions. The preferred alternative which represents a combination of these measures was analyzed for its effectiveness again by continuous simulations. The continuous simulation for this future condition was done for the same five summer periods as used for the existing system assessment. However, in order to check if above criteria were met it was acceptable to only investigate the winter period of rainfalls which had effected the worst impact on receiving waters under existing conditions.

TORONTO, ONTARIO, CANADA

A QQS study has been carried out for the City of Toronto, Ontario, Canada, located on the shores of Lake Ontario. The storm and combined sewer system studied serves an area of about 6,630 ha with 536,000 inhabitants (Figure 45).

As a relief measure for two interceptor sewers constructed more than 60 years ago, construction of a new interceptor, the "Mid Toronto Interceptor", and three interconnecting sewers linking the three interceptor sewers together was recently completed. The maximum conveyance capacity of the new interceptor together with present inflows of all existing inflows to the treatment plant during storms would exceed the capacity of the plant. Accordingly remote controlled, power operated gates in the interconnecting sewers and conventional fixed gates for 24 inflow connection to the new interceptor are used to limit the inflow to meet available capacities at the treatment plant.

Objectives of the study were to assess the impact of the operational behavior of the Interceptor and its effect on the City's sewer network and the treatment plant. In addition annual peak and total quantity and quality discharges to the Lake, the Harbour and the Don River originating from the combined sewer system and the road storm sewer system connected to it were to be computed for the chosen operational scheme. For the selected pumping configuration maximum and annual total flows to the Treatment Plan were also determined.

A family of four representative recorded rainfall events, was used to examine the behavior of the Interceptor system under various gate settings.

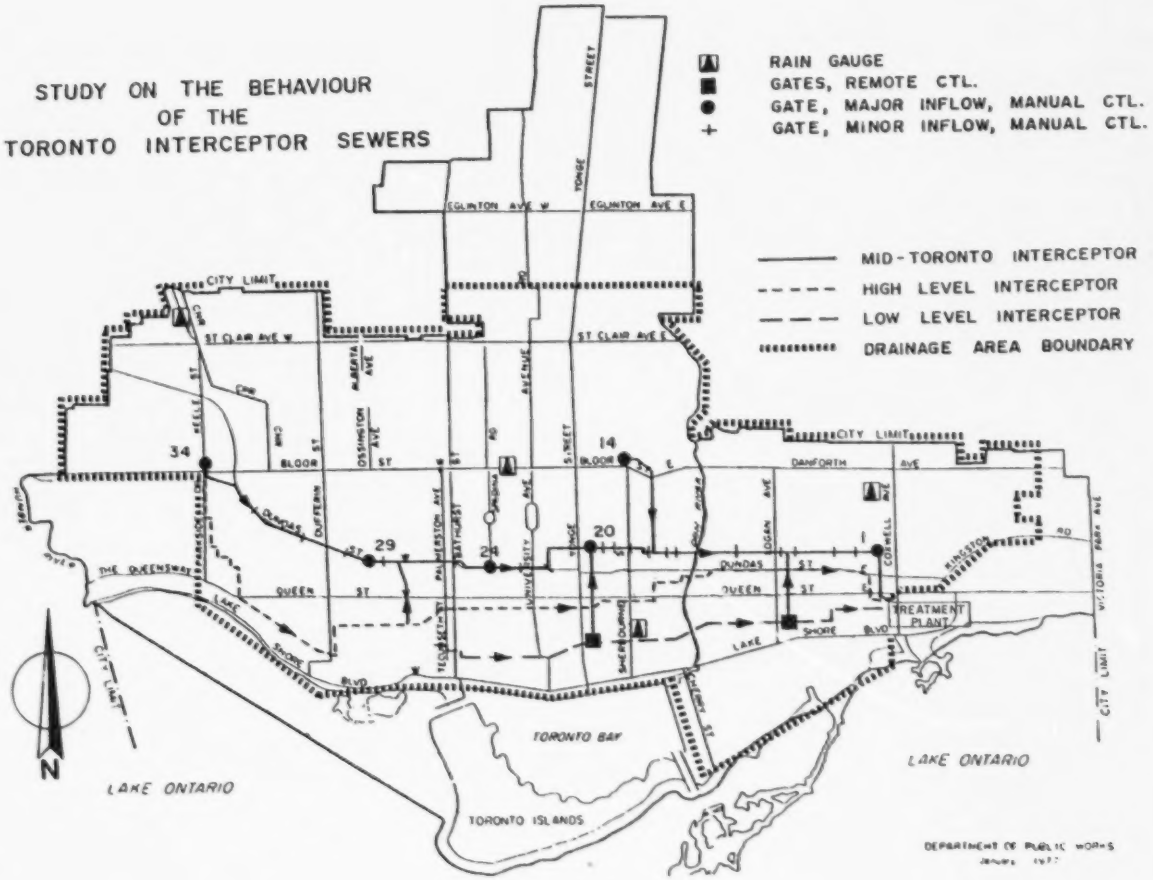

Figure 45. Combined and separate sewer system of Toronto, Ont., Canada, as prepared for QQS simulations.

A continuous simulation for four selected years of rainfall records was carried out for one selected configuration of gate settings.

For calibration of the QQS model measured runoff from two residential catchment areas and several storm events were available. In addition detailed HVM simulation results for model storms of one year and two year return frequency and several measured rainfall-runoff events were used for comparison with QQS simulation results. The QQS program had been adjusted to accommodate for the study area size.

In the future it is intended to use the overflowing loads of BOD_5 and settleable solids calculated by the QQS program as input for another purpose made mathematical model which assesses and predicts the pollutant load distribution within the harbour area of Toronto.

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